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Robert E. Sampson and George S. Springer

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College of Engineering
Ann Arbor, Michigan 48104

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EFFECTS OF TEMPERATURE AND FUEL LEAD CONTENT ON PARTICULATE FORMATION IN SPARK IGNITION ENGINE EXHAUST

Robert E. Sampson

George S. Springer

April 1972

FLUID DYNAMICS LABORATORY
DEPARTMENT OF MECHANICAL ENGINEERING
COLLEGE OF ENGINEERING
THE UNIVERSITY OF MICHIGAN
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ABSTRACT

Experiments were performed to determine the effects of temperature and lead content of the fuel on the weight and size distribution of particulates emitted from a spark ignition engine. The measurements were made using three different, specially constructed sampling systems which utilized filters and an Andersen Sampler for particle collection, and allowed sampling directly from the exhaust stream. The performance of these sampling systems was evaluated, and the conditions necessary for obtaining a representative sample of the exhaust stream were established.

Using both leaded and unleaded fuels, the weight and size distributions of particles in the exhaust stream were measured in the temperature range of 85 to 820°F. The total weight of particles emitted using leaded fuel was approximately six times higher than with unleaded fuel. Temperature was also found to have an effect on the weight of particles in the exhaust stream. When using leaded fuel, a sharp increase in the weight was observed when the gas was cooled below 700°F, a phenomenon attributed to the condensation of lead compounds. This increase did not occur when unleaded fuel was used.

The weight of particles with diameter larger than 0.3 microns was approximately the same for both fuels used. However, the weight of the small particles (diameter less than 0.3μ) was significantly higher when using leaded fuel than when using unleaded fuel.

Particulate deposition on the inside of the exhaust system was also evaluated. The rate of weight deposition along the exhaust system was found to depend upon both the temperature and the fuel used. In the range of the present experiments, less than 10% by weight of the particulates formed in the exhaust stream were deposited on the walls of the exhaust system.

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CHAPTER I

INTRODUCTION

Particulate matter formed in the exhaust of spark ignition engines contributes to the pollution of the environment directly by increasing the particulate content of the atmosphere and indirectly by hindering the performance of the devices controlling gaseous emissions*. For these reasons, it is desirable to control the amount of particulates emitted from spark ignition engines. This could be best achieved by controlling the parameters which affect the formation of particulates. These parameters include the engine operating conditions, the exhaust system, and the fuel (Table I). For optimum results, the influence of each of these parameters upon the physical and chemical characteristics of the emitted particulates should be known. In this investigation, the roles of two of these parameters, temperature and lead content of the fuel, were examined in detail and their effects upon the weight and size distribution were evaluated. These two parameters were selected because of their significance in the particulate formation process. The specific objectives of this study are described following a brief survey of the literature.

A. Literature Survey

Previous investigations of particulate emissions from spark ignition engines may be divided into two categories: 1) measurements made using the samples collected from the environment, and 2) measurements made using samples collected at the exhaust exit. Samples collected

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* Particulate or particle is here defined as any chemical compound, except uncombined water, that is dispersed in a gas phase as either solid or liquid in which the individual aggregates are larger than single molecules ($2.0 * 10^{-4}$ microns in diameter) but smaller than 500 microns diameter.

TABLE I

PARAMETERS INFLUENCING PARTICULATE EMISSIONS

1. Fuel Composition
2. Engine
   a) Design
   b) Wear and Maintenance
   c) Oil
3. Engine Operating Conditions
   a) Speed
   b) Load
   c) Spark Timing
   d) Fuel-Air Ratio
4. Exhaust System
   a) Geometry and Design
   b) Surface
   c) Pressure
   d) Temperature

from the environment were used by many investigators (2-8) to assess the particulate contribution of spark ignition engines to environmental pollution.

Motto et al. (2) and Lagerwerff and Specht (3) measured the lead concentration in vegetation near highways. Einbrodt et al. (4) compared the lead concentration in the lungs of city dwellers with those of people from rural areas. Lazrus et al. (5) related the lead content of precipitation to gasoline sales in different areas. Concentration of particulates suspended in the atmosphere was measured by Larsen and Kanopinski(6) in the Sumner Tunnel, and Colucci and Begeman (7) and Daines (8) near heavily traveled highways.

The results of the foregoing studies (2-8) revealed that particulate effects depend strongly on traffic volume and on distance from the highway. These studies did not, however, provide direct information on the mechanics of particulate formation or on the effects of any of the parameters listed in Table I.

Samples taken directly from the exhaust of spark ignition engines have been analyzed by many investigators (9-18). The influence of engine make on the weight, size, and chemical composition of particulate emissions was investigated by Mueller et al. (9) and Ter Haar et al.(10). Engine make, maintenance, and speed effects on the weight of particles emitted were studied by McKee and McMahon (11). The dependence of particle composition and weight on engine speed was studied by Mueller et al. (9), Lee et al. (12) and Hirschler et al. (13, 14).

The effects of fuel composition upon the physical and chemical characteristics of particulates were evaluated in references 9, 12, and 15-18. The dependence of particle size and weight on fuel composition was

investigated by Mueller et al. (9), Ter Haar et al. (12), Moran and Manary (15), Ninomiya et al. (16), and Habibi et al. (17, 18). Variation of chemical composition of particulates with leaded and unleaded fuels was reported in references 9, 12, 15 and 17. These investigations (9-18)revealed that the weight of particulate emissions is considerably reduced when low lead content fuels are used.

The weight and size distribution dependence of particulate matter upon exhaust stream temperature has not yet been investigated for either leaded or unleaded fuels. There are indirect evidences, however, that the exhaust stream temperature is an important factor in the formation of particulates. The experiments of Ninomiya et al. and Ter Haar et al. indicated that cold cycle operation gives significantly higher emission rates than hot cycle operation. In the previous investigations, the exhaust gas was always cooled below 250°F before being analyzed for particle content. Therefore, the influence of temperature on the particle formation cannot be evaluated from these data. It is evident that the effect of temperature on the size and amount of particulate emissions using both leaded and unleaded fuels merits further consideration.

B. Objective

The major objectives of this investigation were: 1) to develop experimental techniques and apparatus suitable for collecting particles at temperatures up to 850°F and for determining the total weight and size distribution of the collected particles, and 2) to determine the effect of temperature and lead content of the fuel on the total amount and size distribution of particulates emitted from spark ignition engines.

It is recognized that besides temperature and fuel, all other parameters listed in Table I may also influence particulate emissions. However, in order to focus attention on the effects of temperature and fuel, only these two parameters were varied during the experiments. All other parameters were held constant at values representative of an automobile cruising at 55 miles per hour.

CHAPTER II

EXPERIMENTAL APPARATUS

The experimental apparatus consisted of three major components, 1) the engine, 2) the exhaust system, and 3) the sampling system. Each of these components will be discussed in detail in the following sections.

A. Engine

The engine was a 350 cubic inch displacement Chevrolet V-8 production engine. The specifications for this engine are presented in Appendix A.

The engine was mounted on a Midwest Dynamic eddy current dynamometer test stand located in a test cell at The University of Michigan Automotive Engineering Laboratory. The engine and dynamometer were completely instrumented to monitor and control coolant temperature, oil temperature, oil pressure, manifold vacuum, exhaust pressure, engine speed and load. The rate of air flow to the engine was measured by a rounded approach air cart manufactured by General Motors Corporation. The fuel flow rate was measured utilizing a burette type apparatus.

Standard Permalube 10W30 lubricating engine oil was used in the engine. This oil was chosen because it contains few additives (thus minimizing its contribution to emitted particulates), yet it is representative of oils commonly used. The oil was changed at regular intervals (~50 hours of operation) and whenever the fuel was changed. The physical properties of this oil are included in Appendix BI.

Both a "leaded" and an "unleaded" fuel were used in the experiments. The leaded fuel was Standard Regular and the unleaded one was Indolene Clear. The specifications of these fuels are given in Appendices BII and BIII.

B. Exhaust System

The exhaust system consisted of 1) two exhaust manifolds, 2) a crossover pipe, 3) a surge tank, 4) an exhaust to the external vent, 5) a bypass filter, and 6) a simulated exhaust system (Figure 1). The exhaust manifolds were manufactured by General Motors Corporation as standard equipment for the 350 cubic inch engine. A 1/8 inch hole* was located in the left exhaust manifold, 3 inches from the exhaust port of number one cylinder.

The two manifolds were attached to a standard (model AP 3Y7103) crossover pipe. Thus, the exhaust from all eight cylinders was fed into the system, minimizing pressure and velocity fluctuations. To further reduce these fluctuations, a 2 foot long, 1 foot diameter cylindrical surge tank (made of 1/16 inch thick cold rolled steel) was attached to the crossover pipe by a 1 foot long flexible tube. The surge tank was mounted with its axis horizontal. Two 1/4 inch holes were located in the flange connecting the surge tank and the flexible tube. One of these holes was for a thermocouple and one for a pressure gauge. The surge tank was insulated to maintain a temperature drop along it similar to that normally obtained in a muffler. Note, however, a muffler was not included in the exhaust system.

Following the surge tank, the exhaust was discharged into a tunnel vent in the floor of the test cell in one of three ways: 1) directly, 2) through a bypass filter, or 3) through a simulated exhaust system. The three discharge systems were connected to the surge tank by a 14 inch long, 2 inch diameter pipe. Eleven inches from the surge tank, 1/4 inch

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* All hole sizes given herein refer to nominal pipe thread size. All holes were plugged with pipe plugs when not used for sampling.

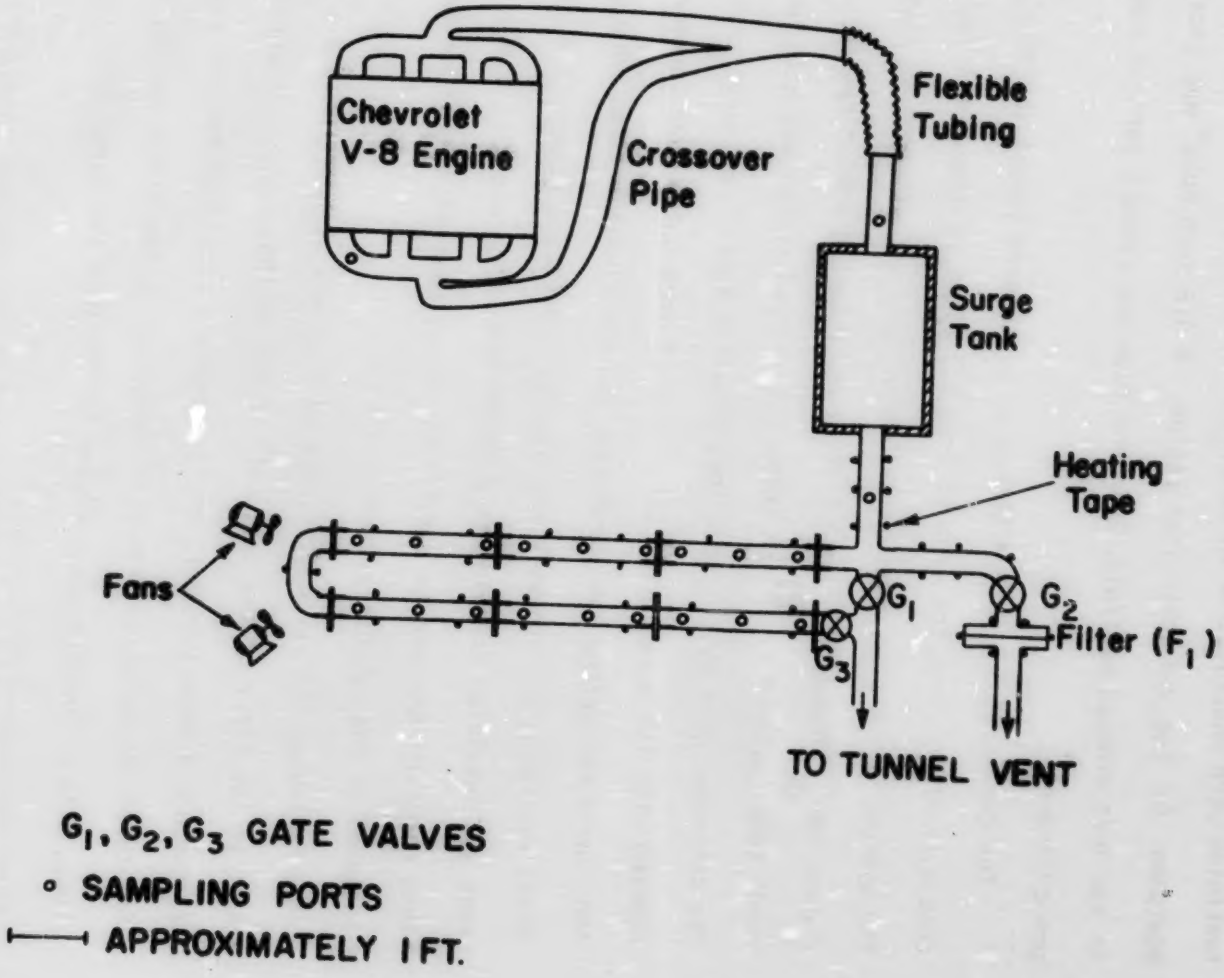


Figure 1: Schematic of Exhaust System

holes (for thermocouples) were provided in the top and side of the pipe.

The three discharge systems were constructed of 2 inch black iron pipe and were coupled by standard 2 inch pipe fittings and flanges. The flange connections were sealed using Cranite high temperature full face seals.

The direction of the flow was controlled by three Crane 2 inch forged steel gate valves (G_1, G_2, and G_3, Figure 1). Valve G_1 controlled the flow to the tunnel vent, and valve G_2 controlled the flow through a bypass filter which was located 32 inches from the surge tank. This filter was a 142 millimeter diameter type A Gelman glass fiber filter mounted in a specially constructed filter holder. Since commercially available filter holders were not capable of withstanding temperatures above 450°F, a special holder was constructed as described in Appendix C. Two inches before and after the filter holder, two 1/8 inch holes (for thermocouples) were provided in the side of the pipe connecting the filter to the exhaust system. The entire bypass system was wrapped with Samox heating tape for temperature control.

Flow to the simulated exhaust system was controlled by valve G_3 (Figure 1). The exhaust system was horizontally mounted and consisted of three 2 foot long pipe sections in series, followed by a 90° pipe elbow, a 3 inch long pipe section, another 90° pipe elbow, and then three more 2 foot long pipe sections in parallel with the first three. All components were connected by flanges.

Each of the 2 foot long sections contained six holes. Three of the holes were 1/8 inch and were located along the top of the pipe at 4, 12, and 20 inches from the upstream end. Three of the holes were 1/4 inch

and were located along the side of the pipe also at 4, 12 and 20 inches from the upstream end. The smaller holes were for thermocouples and the larger ones for sampling probes.

In order to collect deposits on the wall, inserts were placed in each end of the 2 foot long pipe sections. These inserts were made of 0.003 inch thick, 6.5 inch long, 6.0 inch wide stainless steel shim stock. The shim stock was rolled into a cylindrical shape, fitted tightly into the exhaust pipe, and fastened with two number 10-24 machine screws into the wall of the pipe.

The temperature of the entire exhaust system was controlled by Samox heating tapes wound around the exhaust pipe. Voltage to the heating tapes was controlled by a Cole Palmer model 2600 Voltage Controller. The temperature of the exhaust pipe was measured by ten chromel alumel thermocouples cemented in 0.050 inch diameter, 0.115 inch deep holes in the wall of the pipes at 72, 87, 110, 125, 142, 175, 187, 200, 215 and 230 inches downstream from the exhaust manifold. The exhaust gas temperature was measured using six chromel alumel thermocouples inserted directly into the middle of the exhaust stream through the 1/8 inch holes located at 82, 105, 150, 177, 202, and 227 inches from the exhaust manifold.

C. Sampling System

The sampling system consisted of 1) the probe, 2) the particle collection system, 3) the flow measurement apparatus, and 4) the vacuum pump (Figure 2).

1) Probe

The gas sample containing the particles was drawn from the exhaust stream through a sampling probe. Five different sampling probes made of stainless steel tubing were used. The probe dimensions are summarized in Table II.

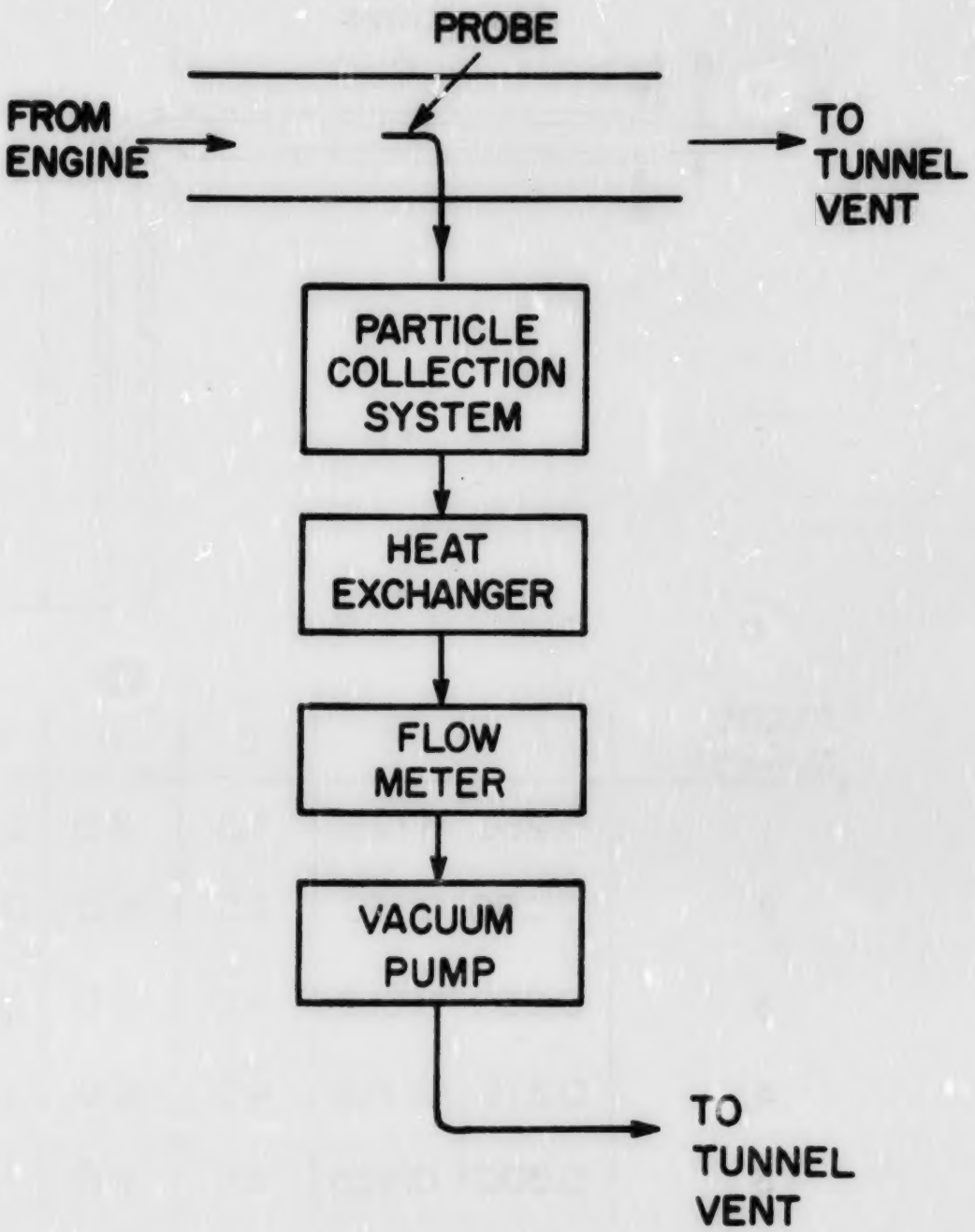
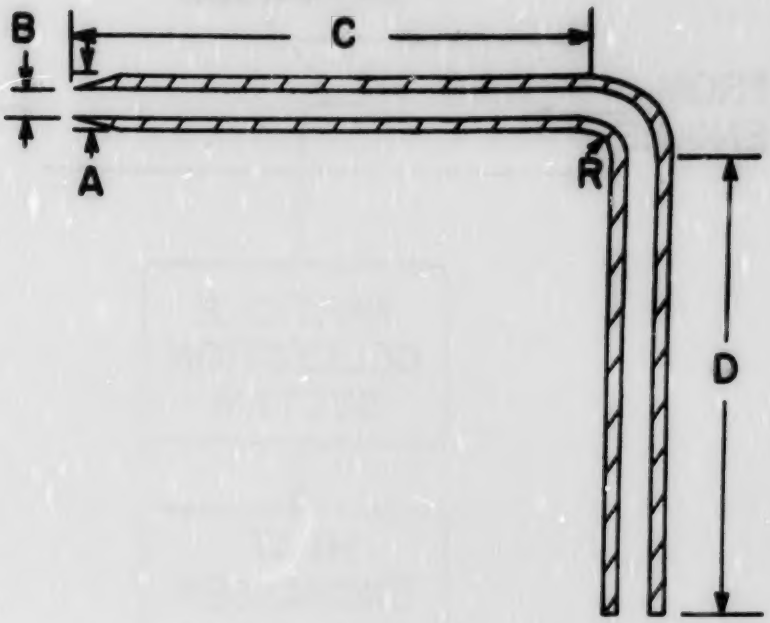


Figure 2: Schematic of Sampling Apparatus

TABLE II

PROBE DIMENSIONS



PROBE NUMBER	A	B	C	D	R
1	0.250	0.125	2.0	6.0	0.50
2	0.250	0.150	2.5	6.0	0.50
3	0.250	0.210	3.0	6.0	0.50
4	0.375	0.335	4.5	6.0	1.00
5	0.500	0.425	5.5	6.0	1.50

ALL UNITS IN INCHES

2) Particle Collection System

Three different particle collection systems were utilized in this investigation (Figure 3). In System I the total weight and size distribution of the particles were measured at temperatures corresponding to the gas temperature in the exhaust stream. In Systems II and III the total weight of particles could be determined at temperatures below the gas stream temperature. In System II the sample was cooled by water. In System III the sample was mixed with ambient air, thereby the sample temperature was reduced to levels below those obtainable in System II.

System I consisted of an Andersen Sampler (Appendix D) and a backup filter, connected in parallel with a bypass system (Figure 3a). Flow to the sampler and bypass was controlled by two 3/8 inch stainless steel gate valves connected to the probe by a 1/4 inch to 3/8 inch stainless steel connector.

The sampler was connected directly to one of the gate valves by a 3/8 inch stainless steel pipe nipple and a 3/8 inch to 1/2 inch stainless steel reducing bushing.

A chromel-alumel thermocouple was inserted into the middle of the gas stream through the wall of the nipple. The Andersen Sampler was a model 50-000 high temperature stack sampler with inconel gaskets and stainless steel separating plates. Its particle collection characteristics are summarized in Appendix D. A backup filter was placed behind the sampler to collect the particles too small (aerodynamic diameter* less than 0.3 microns) to be collected by the sampler. The filters used were 47 millimeter Gelman type A glass fiber filters. These filters were 99% efficient in removing particles of diameter larger than 0.05 microns.

* a particle having an aerodynamic diameter D, experiences the same forces in a fluid as a sphere of diameter D having a density of 1 gm/cm^3.

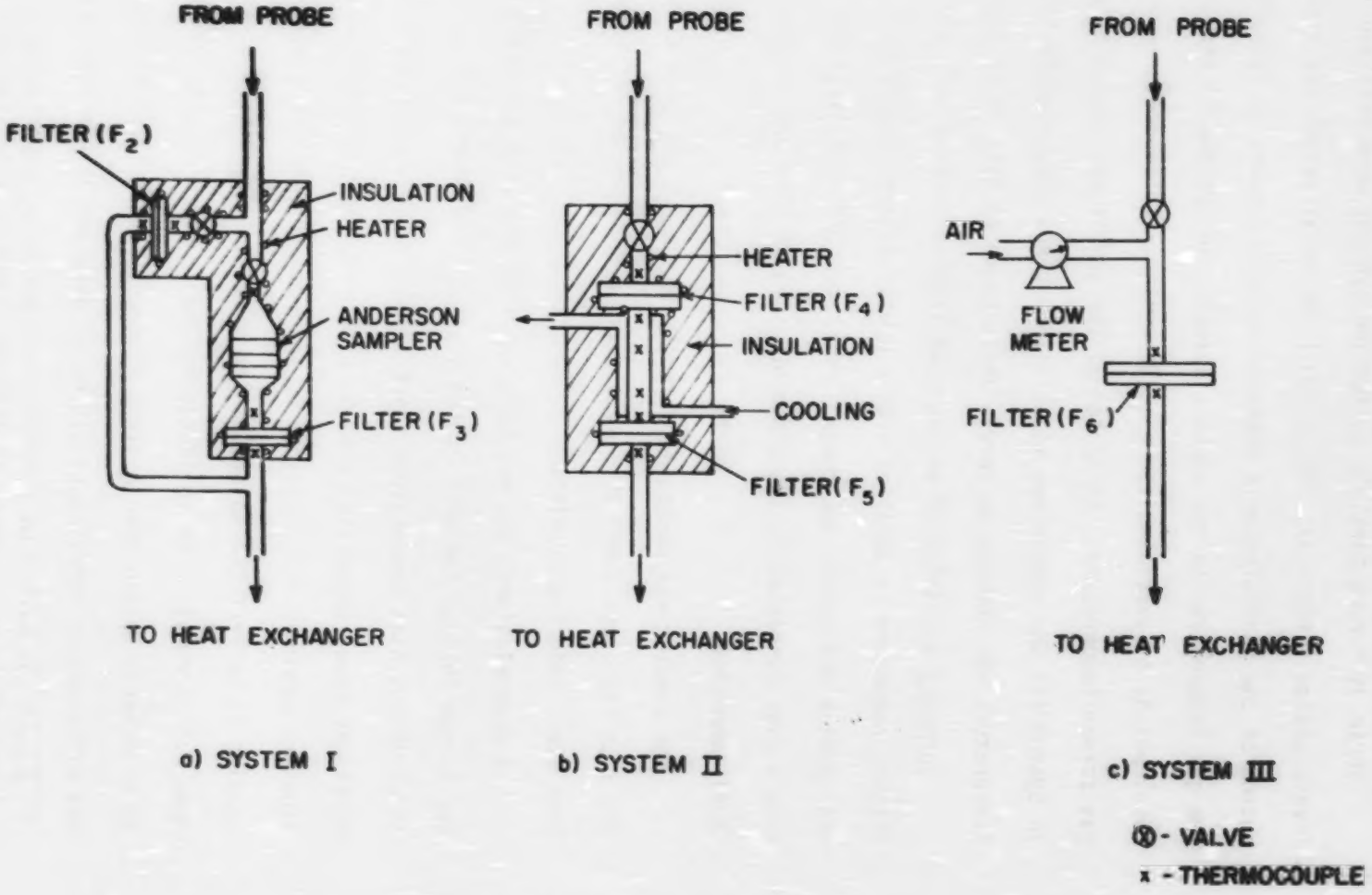


Figure 3: Schematic of Particle Collection Systems

Commercially available filter holders were incapable of withstanding the temperatures (~850°F) encountered in the experiments so a special one was constructed as described in Appendix C. The filter holder was connected directly to the sampler through a 3/8 inch to 1/2 inch stainless steel reducing bushing.

The bypass filter system consisted of a filter and filter holder identical to the one behind the sampler (see above). This filter holder was attached directly to a second gate valve.

The entire particle collection system was surrounded with beaded heaters and 1 inch thick Kaowool ceramic fiber insulation designed to allow the system to reach temperatures of 850°F. The heaters were controlled by Cole Palmer model 2600 voltage controllers. The temperature was monitored using thermocouples located as indicated in Figure 3.

System II consisted of a 10 inch long, 3/16 inch diameter, 0.016 inch thick stainless steel tube placed between two Gelman type A 47 millimeter glass fiber filters (Figure 3b). These filters were mounted in filter holders described in Appendix C. The tube was surrounded by a 1 inch diameter, 0.095 inch thick, 10 inch long stainless steel tube. This tube was connected to a water line by a metering valve to allow water circulation between the tubes. By controlling the water flow rate, the temperature of the gas could be adjusted from 850°F to 150°F. Thermocouples were inserted into the gas stream directly behind the first filter and in front of the second one. The entire system was enclosed in beaded heaters and insulation. Thermocouples were provided for temperature monitoring.

In System III, a 47 millimeter Gelman type A glass fiber filter mounted in a commercial Gelman model 2220 filter holder was connected to the probe through a 1/4 inch diameter, 5 inch long stainless steel tube

(Figure 3c). A 1/4 inch Swaglok stainless steel metering valve was contained in this section for precise control of the flow. Ambient air could be mixed with the gas sample through a 1/4 inch diameter, 2 foot long stainless steel tube connected to the sample line between the valve and the filter. The air flow rate was measured by a wet test meter (American Meter Company model 803) at the inlet of the air line.

3) Flow Measurement Apparatus

The flow through each of the sampling systems was measured by a wet test meter (American Meter Company model 803). To reduce the temperature of the exhaust gas to approximately 70°F, a heat exchanger cooled by water was placed between the wet test meter and the particle collection system. 1/4 inch copper tubing was used to connect the wet test meter to the particle collection apparatus.

4) Vacuum Pump

Flow through the sampling system was provided by an Edwards High Vacuum Limited Speedivac ED-150 vacuum pump. This was attached to the wet test meter by 1/2 inch tygon tubing. A bleed valve open to the ambient was installed in this line to control the flow rate.

CHAPTER III

EXPERIMENTAL PROCEDURE

Once the engine was installed, it was operated for 50 hours at various speeds as recommended by the manufacturer (19). During this time the engine exhaust was discharged directly into the tunnel vent through valve G_1 (Figure 1). After the engine was "broken in," all experiments were performed at a steady engine speed (1800 rpm) and constant load (24.5 bhp), corresponding to a 1970 full sized Chevrolet cruising at 55 mph under road load conditions (see Appendix G). The load on the engine was calculated from the expression (20),

$$\text{load} = \frac{V}{375}(0.012\ W + 0.00125\ AV^2) \qquad \text{bhp}$$

where V is the vehicle speed (55 mph), W is the total car weight (4000 lbs), and A is the automobile front projected area (31 ft^2). The numerical values for weight and projected area were those specified by the automobile manufacturer (21).

A. Calibration Tests

Prior to undertaking the experiments, a series of tests were conducted to ensure that the sample drawn from the exhaust stream was representative of the conditions in the stream itself. In these tests, leaded fuel was used, and the particles were collected utilizing Sampling System II. The Samples collected on the filters were analyzed as described in Section IIIC. In all of the calibration tests, the temperature of the sampling system was regulated so that the first filter (F_4, Figure 3b) was at 820°F and the second one F_5, Figure 3b) at 660°F or 700°F. Before collecting a sample, the engine was always warmed up for 30 to 40 minutes (Appendix A).

When sampling directly from the exhaust stream, it is of primary importance that the sample be withdrawn isokinetically(22). For isokinetic sampling the flow velocity at the inlet of the probe must be equal to the gas stream velocity at the same point. Such conditions can be achieved only in steady flow, which does not exist in an automobile exhaust system.

To determine the effects of velocity fluctuations on the concentration of particulates in the sample, the exhaust stream was sampled at two different points: a) directly in the exhaust port of number one cylinder, and b) 100 inches downstream from the exhaust port. The particle concentrations thus measured were compared to the particle concentrations in the exhaust stream as determined by the filter collecting particles from the entire exhaust stream (F_1 in Figure 1). The sample taken 100 inches downstream from the exhaust port yielded very similar results to the exhaust stream filter (Table III). This indicates that by this point fluctuations were damped sufficiently so as not to affect the sample appreciably. It is noteworthy that even the sample taken directly from the exhaust port agrees within 10% of the sample collected from the exhaust stream by filter F_1.

Although fluctuations do not appear to be a significant factor, a 2 cubic foot volume surge tank was placed in the exhaust system to further minimize their effects. It was found that with the surge tank in the system the fluctuations in static and stagnation pressures were reduced by a factor of 10 (Table IV). These measurements were made immediately after the surge tank (Figure 1), using a Consolidated Electrodynamic type 4-312-002 quartz strain gauge pressure transducer with its output recorded on an oscilloscope. While the surge tank reduced the

TABLE III

EFFECT OF SAMPLE PROBE LOCATION

ON PARTICLE CONCENTRATION

	Particle Concentration (mg/ft^3)		
	Exhaust Port*	100 inches* down stream	Filter (F_1)
	0.412	0.394	0.47
	0.374	0.473	0.38
	0.306	0.446	
	0.421	0.358	
Average	0.378	0.417	0.42

* Probe Data

TABLE IV

PRESSURE VARIATIONS AT THE LOCATION

OF THE SURGE TANK (inHg)

	With surge tank		Without surge tank	
	Static	Stagnation	Static	Stagnation
Above Mean	0.15	0.30	1.20	1.80
Below Mean	0.15	0.30	1.20	1.20

pressure fluctuations, it did not appear to influence the measured particle concentration, as indicated by the results in Table V.

Variations in the sampling flow rate may also affect the particle samples. To evaluate this effect, particulate concentrations were measured at various sampling flow rates. The results, shown in Figure 4, reveal that near the flow rates required for isokinetic sampling even 200 to 300% variations in sampling flow rate do not cause more than a 10% difference in the measured particle concentrations. This is in agreement with the theoretical results of Watson (22) which are also shown in Figure 4. In all subsequent tests, samples were collected at isokinetic flow rates (Appendix G).

To determine the effect of the probe diameter on the sample, particulate concentrations were measured using five different size probes (Table II). The results, presented in Figure 5, do not show any systematic variation in particle concentration with probe diameter. In all subsequent tests, a 1/4 inch outside diameter probe was used (probe 3, Table II).

The distribution of particles across the exhaust stream was evaluated at the first sampling port after the surge tank (Figure 1) by placing the probe at different locations across the pipe as shown in Table VI. The maximum difference in particle concentration across the exhaust stream was found to be 4%. Therefore, in all subsequent measurements, the probe was placed in the center of the stream.

The minimum time required to collect a representative sample on the filters was estimated by measuring particle concentrations at several different sampling durations. The results indicated that 10 minutes was adequate for collecting a representative sample on the filter (Figure 6).

TABLE V

EFFECT OF SURGE TANK

ON PARTICLE CONCENTRATION

Particle Concentration (mg/ft^3)

	With Surge Tank	Without Surge Tank
	0.314	0.394
	0.49	0.473
		0.446
		0.358
Average	0.402	0.417

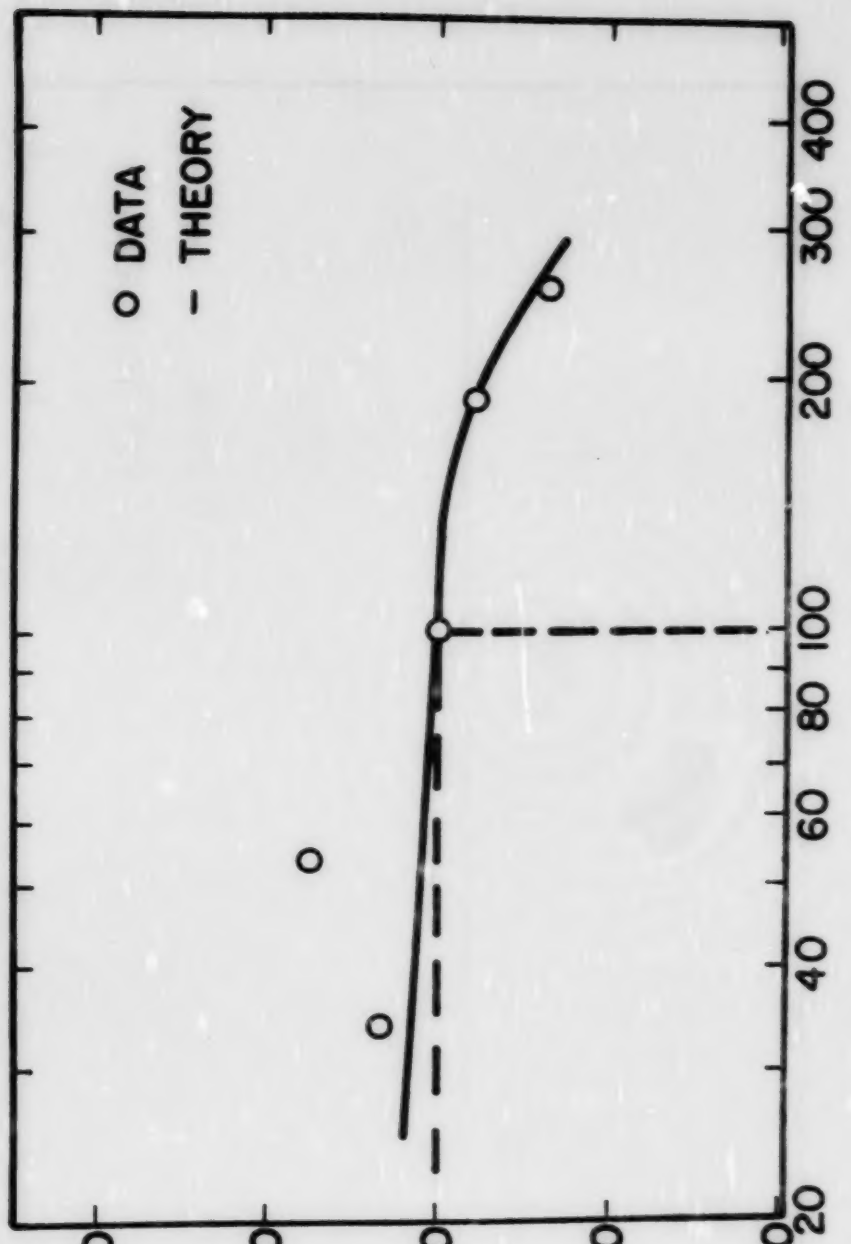


Figure 4: Effect of Sampling Rate Variation on the Measured Particulate Concentration. Theory from Watson (22) for 1.0 micron diameter particles

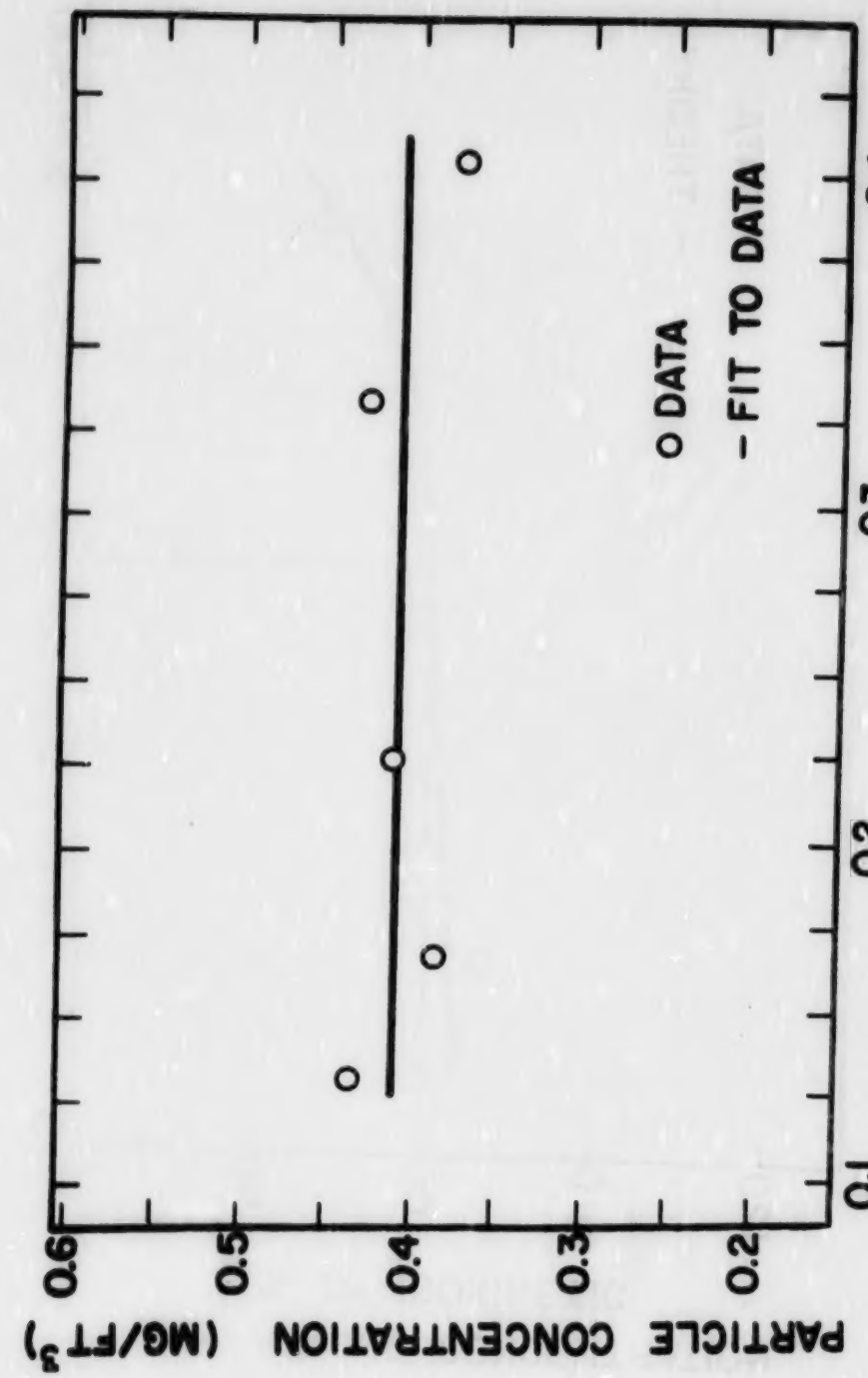


Figure 5: Effect of Probe Size on Measured Particle Concentration. Sampling System II. Second Filter at 700°F

TABLE VI

VARIATION OF PARTICLE CONCENTRATION ACROSS THE EXHAUST STREAM

PROBE LOCATION					
PARTICLE CONCENTRATION (% OF CENTER)	100.0	100.4	98.7	96.5	102.1

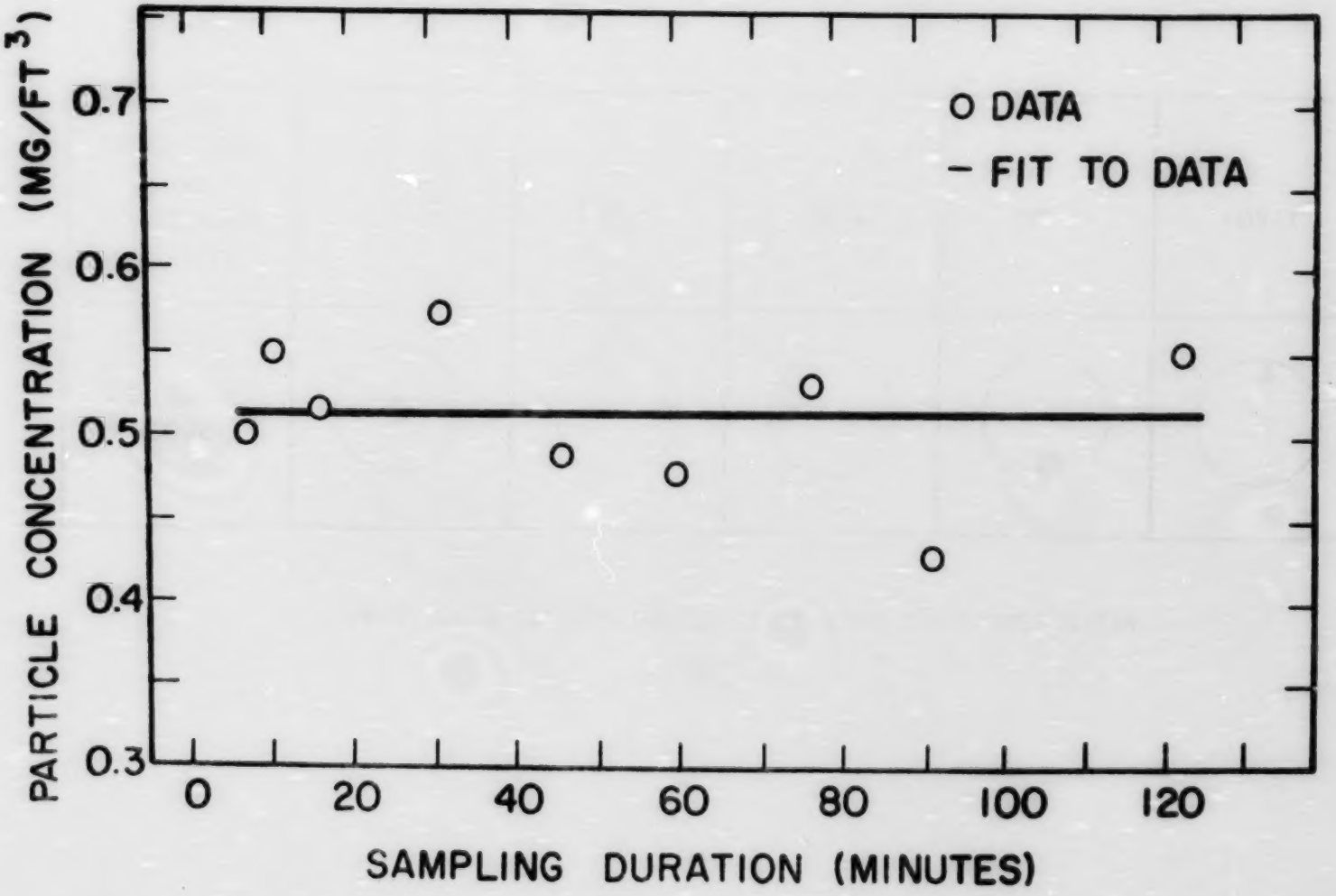


Figure 6: Effect of Sampling Duration. System II, Second Filter at 660°F.

These experiments demonstrated that particle samples collected using this apparatus and procedure were reasonably representative of the particle concentrations in the exhaust stream.

B. Test Procedure

Prior to collecting samples for analysis of particle concentration and size distribution in the exhaust stream, the temperatures of the exhaust gas and the wall of the simulated exhaust system were recorded along the entire exhaust system under steady state conditions (Figure 7). These measurements were performed twice. Once, the exhaust system was exposed to room air and hence cooled by natural convection only. Once it was cooled by forced convection created by fans blowing longitudinally along the exhaust system. The latter was used to simulate conditions that might occur with a moving automobile. The flow was generated by 2 Emerson Electric Company model K60TB fans operated at 1150 rpm, located as indicated in Figure 1.

Data was taken utilizing Sampling Systems I, II and III. With each system the general test procedure was the same. The engine was warmed up for 30 to 40 minutes while discharging through the tunnel vent. During this time, the samplers (Andersen Sampler and filters) were brought to the desired temperature, and the simulated exhaust system was heated to the temperature it would have attained had the exhaust gas been flowing through it. Once steady state temperatures were reached, the main gas stream was switched from the tunnel vent to the simulated exhaust system. Flow through the probe and the sampling system was then initiated and a sample collected.

Sampling duration was 2 hours for the Andersen Sampler, and for the

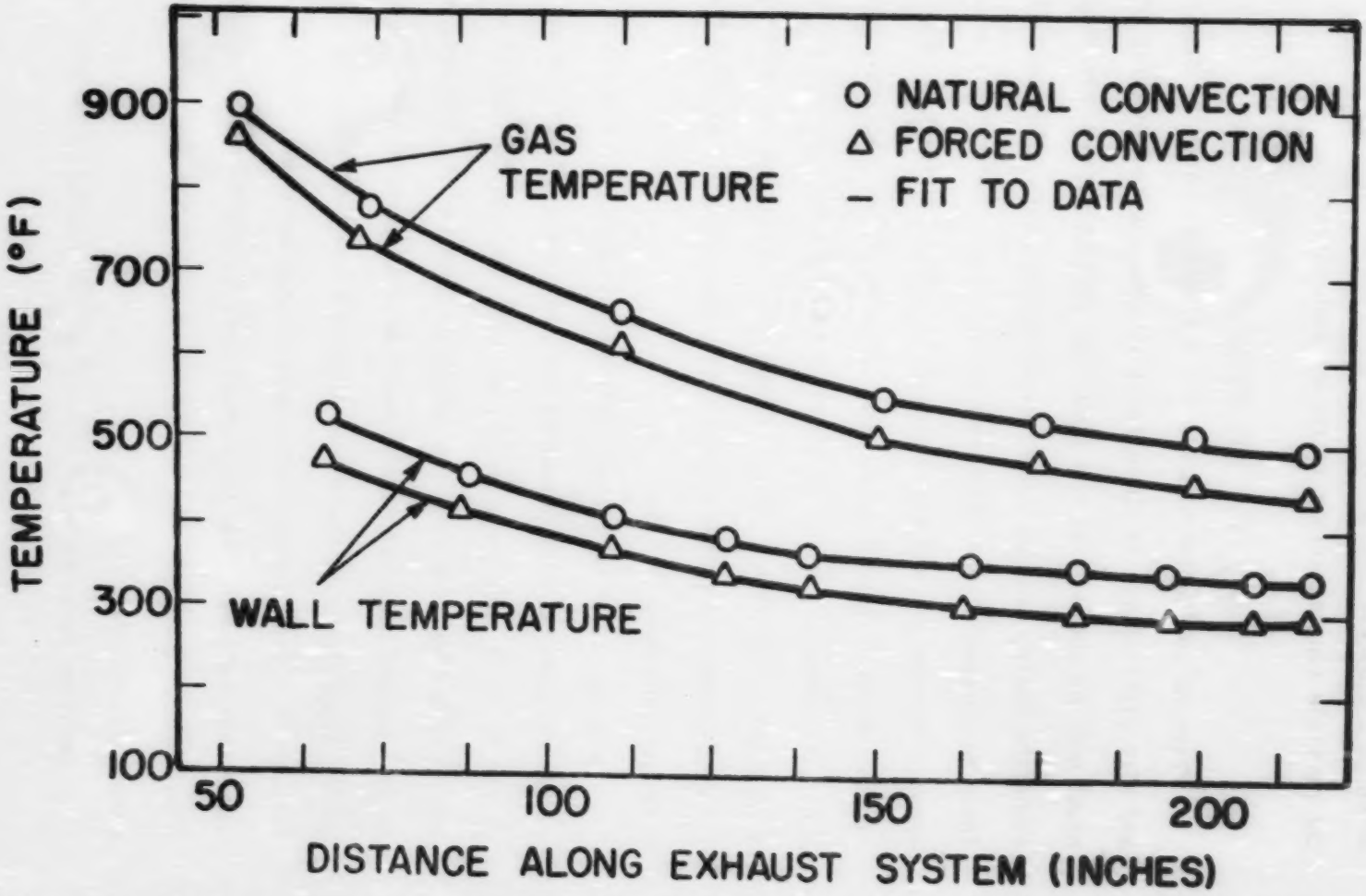


Figure 7: The Temperature Variation of the Exhaust Gas and the Inside Wall of the Exhaust System with Natural and Forced Convection Cooling

filters it was 10 minutes. Handling of the plates and filters is described in Section C.

Using System I, the exhaust system was sampled at 6 locations, approximately 24 inches apart, along the simulated exhaust system. The entire sampling system was kept at the temperature of the gas stream at the location of the sampling probe.

With System III samples were collected at the end of the simulated exhaust system. The ratio of the air to exhaust sample flow rate was 8 to 1.

Before using System III, the particle concentration in ambient air was determined by sampling directly from the atmosphere for 8 hours. A particle concentration of $1.5 * 10^{-4}$ mgs/ft^3 was found in the ambient air. This is less than 0.1% of the particle concentration in the exhaust stream.

Samples were collected with System II at the beginning of the simulated exhaust system. With this apparatus the temperature of the filters was adjusted to different values either by varying the water flow rate or the heater voltages. Measurements were made in the temperature range of 820°F to 450°F.

Deposition on the wall of the exhaust system was studied by placing 12 inserts in the simulated exhaust system and by measuring the weight of the particles deposited during 2 hours. In these tests, while the engine was warming up and discharging into the tunnel vent, the simulated exhaust system was heated with heating tape to the temperature it would have attained had the exhaust been flowing through it. The exhaust from the engine was switched to the simulated exhaust system once steady state conditions were established.

All the experiments described have been repeated 4 times, once using

natural convection and once using forced convection cooling for both leaded and unleaded fuel. When the fuel was changed, the engine was run for 32 hours with the new fuel before the new series of experiments were begun (Appendix A).

C. Data Analysis Procedure

The filters, sampler plates, and exhaust system inserts were handled as follows. Before the experiments, the filters were kept for 24 hours in a constant temperature Buehler Ltd. desicator containing no. 6 Indicating Dririte. The filters were then weighed on a model 6B Mettler analytical balance (precision ±0.01 milligrams) and placed in the filter holders. After completion of a test, the filters were removed from the filter holders and returned to the desicator. The filters were weighed after 24 hours. The weighing was repeated at regular intervals (~24 hours) until there was no change in the weight. To reduce contamination, the filters were always handled with forceps, and each filter was used only once. To determine if collected matter evaporated from the filter inside the desicator, the filter was weighed immediately after the test, then placed in the desicator and weighed again after twenty four hours. This procedure was repeated with six different samples. A weight loss between the two measurements was never observed.

The Andersen Sampler plates and the inserts in the exhaust system were handled in the same manner as the filters. However, these were reused after a thorough cleaning with toluene.

Some of the filters, sampler plates and inserts were viewed under a JEOL-JSM-U3 Scanning Electron Microscope. Prior to viewing, the filters were vapor deposited with chromium. The plates and inserts did not require such special treatment. Secondary electron images obtained using a voltage of 15 KV were recorded on film.

CHAPTER IV

RESULTS

In this section, results are presented describing the effects of temperature and lead content of the fuel on the concentration and size distribution of particles in the exhaust stream, and on the deposition of particles inside the exhaust system. Details of the data on which these results are based, are included in Appendix F.

A. Particle Concentration

The particle concentration as a function of temperature is shown in Figure 8. The results are presented in terms of mg/ft^3 and gm/mile for both leaded and unleaded fuel (see Appendix G). The data were obtained using Sampling Systems I and II above 450°F and Sampling System III at 85°F. The concentrations given in Figure 8 are nearly the same as would be emitted from the exhaust system, since only a small percentage of the particles are deposited on the wall (see Section IVC).

When using leaded fuel the temperature has a significant effect on the concentration of particles (Fig. 8). At 700°F, the particle concentration changes abruptly, increasing markedly with decreasing temperature. This is probably caused by condensation of PbCLBr vapors in the exhaust stream (see Appendix E). The concentration remains constant between 675°F and 450°F, but increases again when the temperature drops from 450° to 85°F. This increase is probably due to the condensation of heavy hydrocarbons in the gas stream. Note that exhaust gases are unlikely to be cooled much below 85°F. Therefore, the concentrations obtained at this temperature are reasonably close to the maximum values that would be emitted in practice from an automobile exhaust.

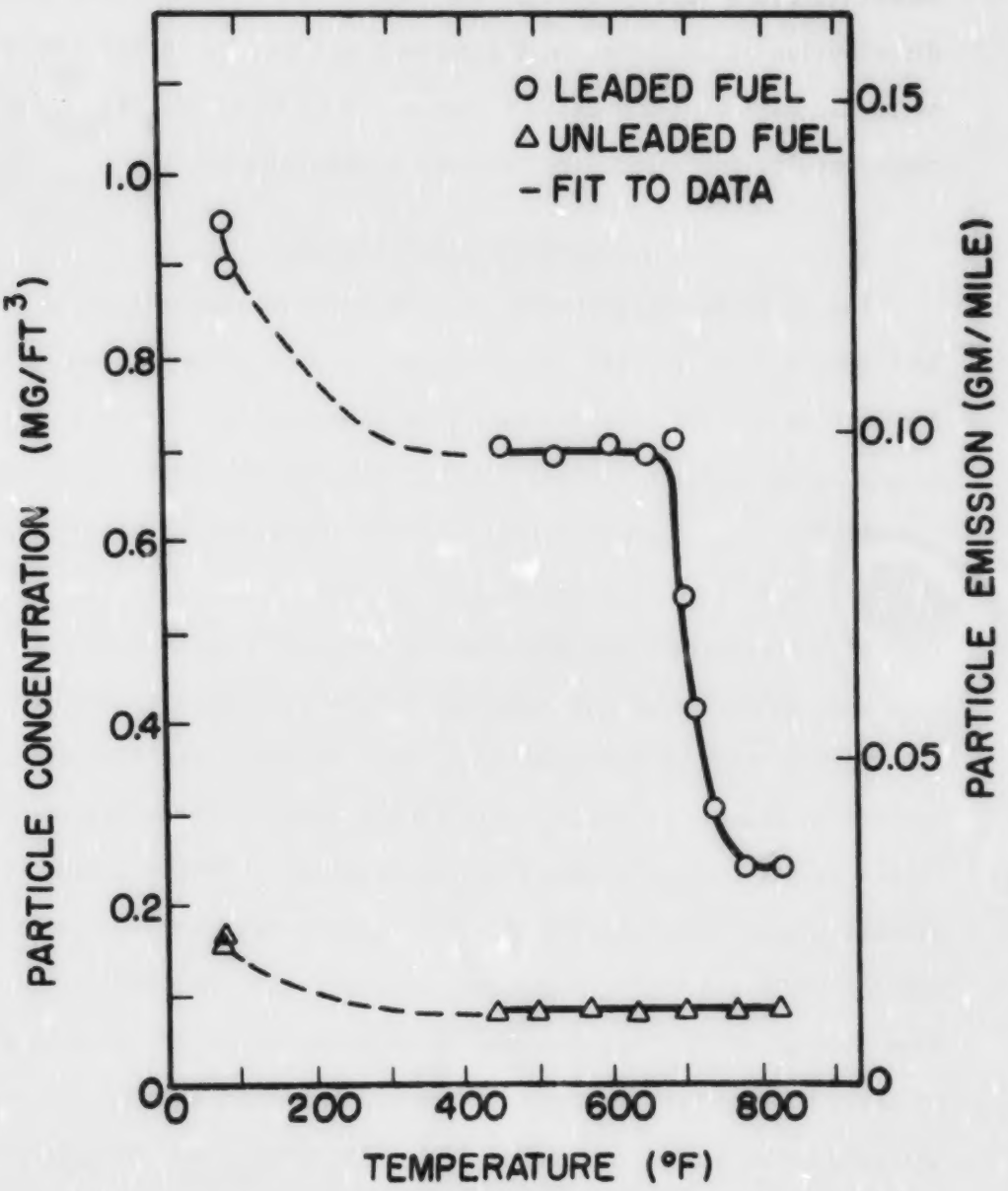


Figure 8: Particle Concentration in Exhaust Stream

When using unleaded fuel, the temperature seems to have little effect on particle concentration at temperatures above 450°F. This suggests that few particles were formed in the exhaust system. Consequently, most particles present in the exhaust stream must have originated in the combustion chamber. Although a chemical analysis of the particles was not performed, earlier studies (e.g. 23 and 24) indicated that such particles are composed mostly of carbon. An increase in particle concentration was observed between the temperatures of 450°F and 85°F, probably due to condensation of heavy hydrocarbons. It is noteworthy that under the steady state conditions of these tests, nearly 6 times fewer particles were emitted with unleaded fuel than with leaded fuel. The difference in particle concentration with leaded and unleaded fuel is attributed to the difference in lead content and fuel hydrocarbon composition.

Figure 8 clearly indicates the effects of temperature and fuel lead content on particle concentration. These results, however, are only for a specific engine operating at a constant speed and at road load conditions. The effects of engine speed and load on the results were not evaluated. These effects can be assessed by comparing the present results with those obtained by other investigators. Comparisons can be performed only with the data taken at 85°F since none of the previous investigators sampled at higher temperatures. The comparisons, given in Table VII, reveal that for both leaded and unleaded fuels, the particle concentrations are nearly the same for different engines and for different speeds, provided the engine speed remained constant. This suggests that the results in Figure 8 are representative of steady operating conditions. During cyclic operating conditions, the particle concentrations are generally higher than during steady state operation, but the ratio of particle concentration with leaded and unleaded fuel is nearly the same as with steady speeds (Table VIII).

TABLE VII

PARTICULATE EMISSIONS AND PARTICLE

CONCENTRATIONS AT STEADY OPERATING CONDITIONS

A

Particulate Emissions (gm/mile)

Investigator	Speed (mph)	Leaded Fuel	Unleaded Fuel	Ratio
Moran & Manary (1970)	60	0.117-0.167	0.0033-0.0167	10:1
McKee & McMahon (1960)	50	0.085-0.295		
Sampson (1972)	55	0.13	0.020	6.5:1

B

Particle Concentrations (mg/ft^3)

Investigator	Speed (mph)	Leaded Fuel
Lee et al. (1970)	50	1.12
Mueller et al. (1962)	25,45 60	0.93
Sampson (1972)	55	0.85-0.94

TABLE VIII

PARTICLE EMISSIONS DURING

CYCLIC OPERATING CONDITIONS

Particle Emissions (gm/mile)

Investigator	Leaded Fuel	Unleaded Fuel	Ratio
Habibi (1970)	0.4	0.15	2.66:1
Ninomiya et al. (1970)	0.35-1.20	0.05-0.5	7:1

B. Size Distribution

Size distributions of particles, as measured by the Anderson Sampler, are presented in Figure 9 and Table IX. In order to demonstrate the effects of fuel composition and temperature, only representative results are shown. Data obtained at additional temperatures were found to be scattered around these curves in a random manner.

Similar to the particle concentration, the size distribution was unaffected by the temperature in the ranges of 450-675°F and 450-820°F for leaded and unleaded fuel respectively. For leaded fuel, there was a change in the particle size distribution at 700°F which is about the same temperature at which a change in particle concentration was noted. The weight of the smaller particles (particles less than 1 micron diameter) is much higher at the lower temperature (500°F) than at the higher temperature (820°F) (see Table IX).

The particle size distributions are significantly different for leaded and unleaded fuel. For leaded fuel, approximately 88% by weight of the particles are smaller than 0.35μ and 98% by weight smaller than 10.0μ. For unleaded fuel, approximately 40% by weight of the particles are smaller than 0.35μ and 88% by weight are smaller than 10.0μ (Figure 9). The weight of small particles (smaller than 0.35μ) is much higher with leaded than with unleaded fuel. However, the weight of large particles (larger than 0.35μ) is approximately the same for both leaded and unleaded fuel (Table IX).

The foregoing results imply that lead compounds exhausted as particulate matter are mostly in particles smaller than 0.35μ. Similar results were obtained by other investigators under both cyclic and steady state operations using different engines (Table X). Note that cyclic

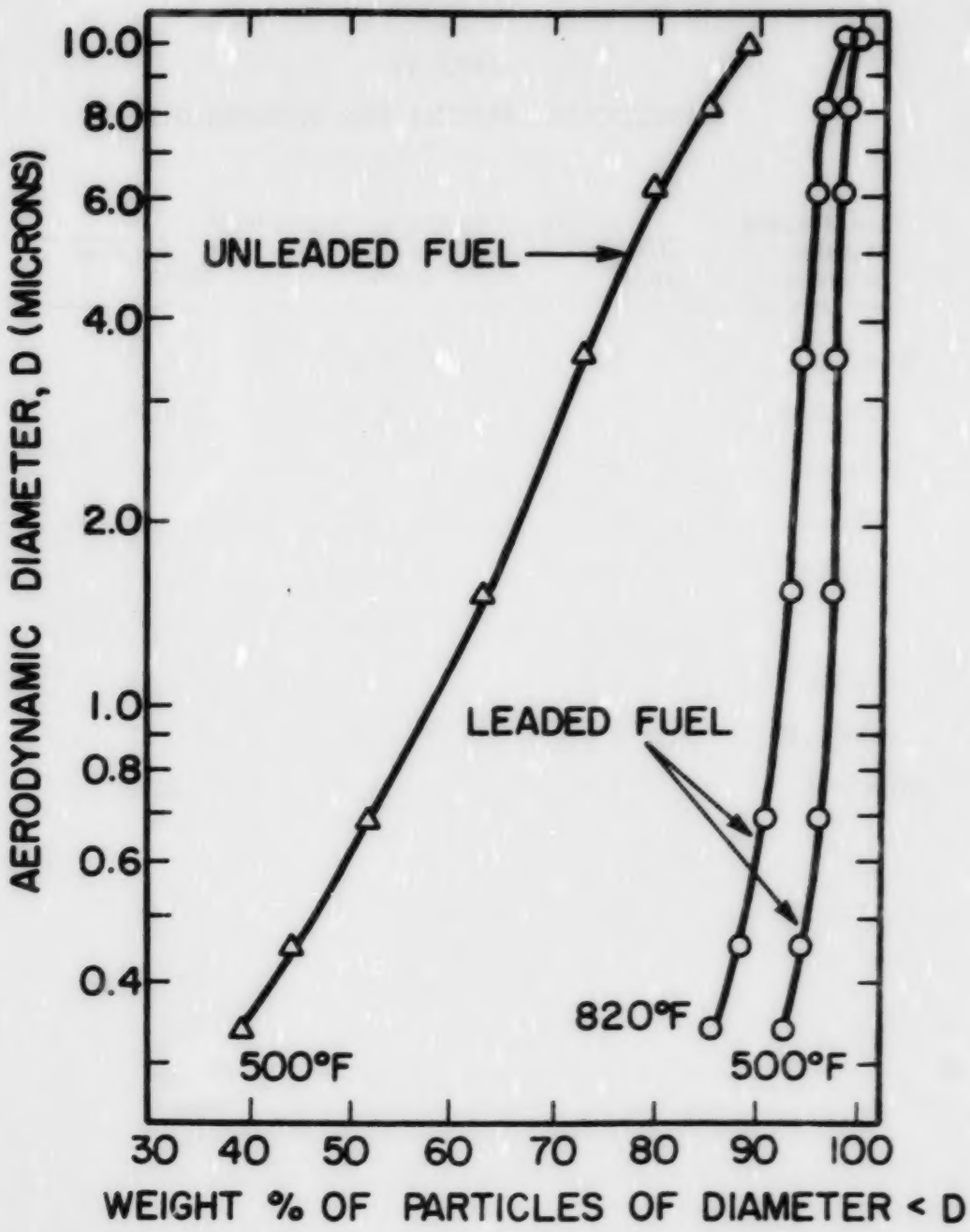


Figure 9: Representative Particle Size Distributions

TABLE IX

REPRESENTATIVE PARTICLE SIZE DISTRIBUTIONS

Aerodynamic Diameter (microns)	Weight of Particles ($mg/ft^3 * 10^2$) Unleaded Fuel 500°F	Leaded Fuel 500°F	Leaded Fuel 820°F
Above 10.0	1.0	0.8	0.45
8.0-10.0	0.4	0.38	0.45
6.0-8.0	0.4	0.34	0.5
3.5-6.0	0.5	0.63	0.35
1.5-3.5	0.8	0.7	0.35
0.7-1.5	0.7	0.33	0.2
0.42-0.7	0.7	0.7	0.25
0.35-0.42	0.4	0.7	0.25
Below 0.35	3.4	51.7	20.5

operation yields larger particles than steady operating conditions. This is felt to be because of agglomeration of particles at the wall and re-entrainment during cyclic operating conditions.

C. Surface Deposition

Particle deposition along the inside surface of the exhaust system was measured using both leaded and unleaded fuels. Deposition is caused by the transport of particles from the gas stream to the wall and by the formation of particles directly on the wall. The former is caused by several mechanisms, including Brownian diffusion, electrostatic, gravitational, thermal, and inertial forces. The latter is due to condensation on the wall, which is generally ~150°F cooler than the gas stream. The deposition rate along the wall depends upon the relative magnitudes of these various effects. When using unleaded fuel, the deposition rate increases along the wall with decreasing wall temperature (Figure 10). Scanning electron microscope photographs taken of the deposition at the beginning and at the end of the exhaust system support this observation (Figure 11).

For leaded fuel, there is a sharp increase in the deposition rate at the point where the wall temperature reaches 500°F (Figure 10). As indicated previously, a large number of particles are formed at this temperature, causing the increase in the deposition rate.

Although the deposition rate is not necessarily uniform along the exhaust system, the total weight of particles deposited along the exhaust system increases uniformly (Figure 12)*. In comparing Figure 12 to Figure 8, it is seen that the weight deposited up to any point in the system is less than 10% of the particles contained in the stream at that point.

* Particle deposition is expressed as weight deposited per cubic foot of exhaust flow per square foot of exhaust system surface.

TABLE X

PARTICLE SIZE DISTRIBUTION RESULTS

FROM OTHER INVESTIGATIONS

Investigator	Operating Condition	Results	
		Leaded Fuel	Unleaded Fuel
Ninomiya et al. (1970)	cyclic	40% of weight in particles smaller than 0.1μ	10% of weight in particles smaller than 0.1μ
Mueller et al. (1962)	steady	68% of weight in particles smaller than 0.3 μ	
Lee et al. (1970)	steady	95% of lead in particles smaller than 0.25μ	
Habibi (1970)	cyclic	40% of lead in particles smaller than 0.25μ	

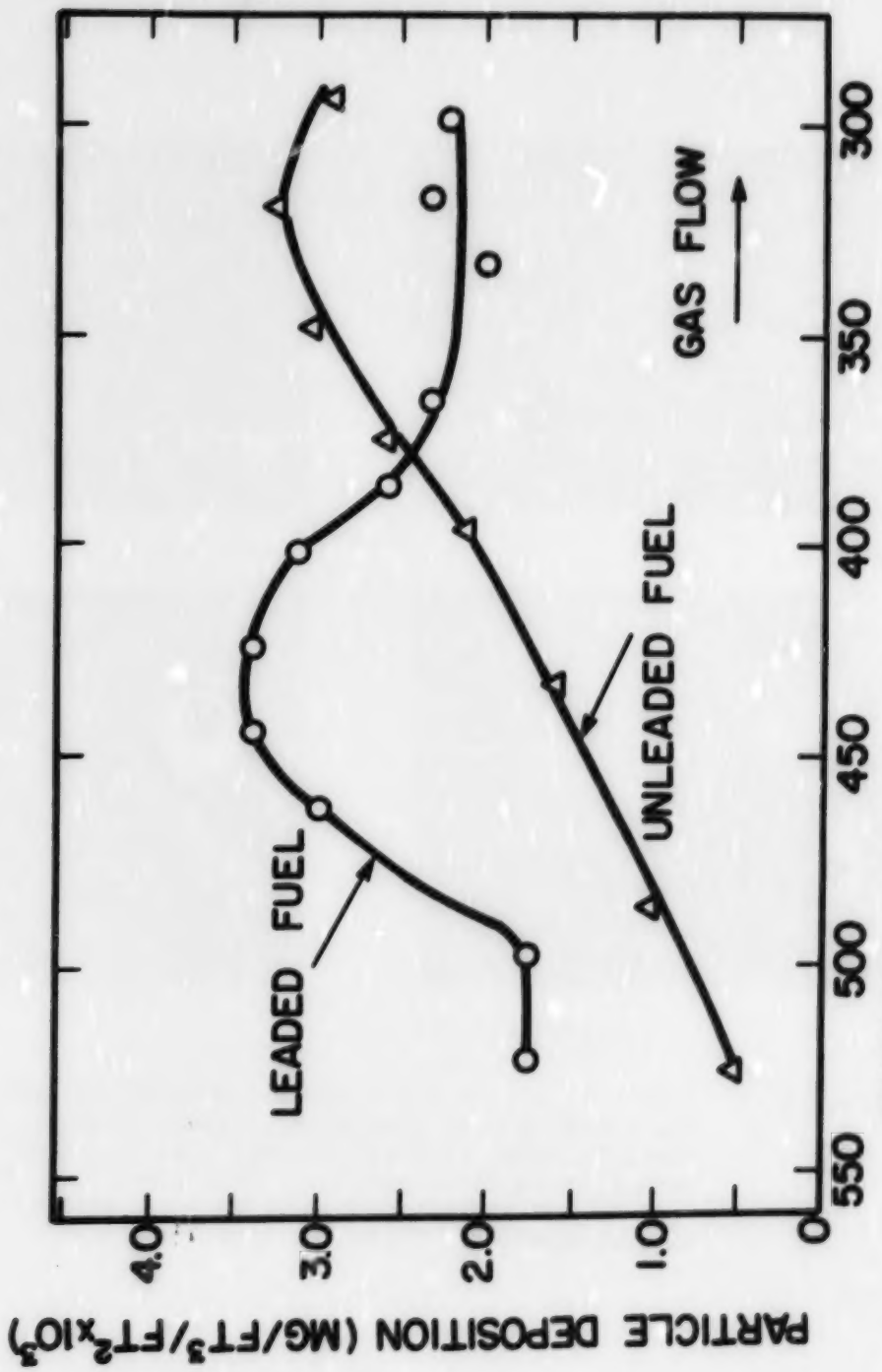


Figure 10: Deposition Rate on the Inside Wall of the Exhaust System

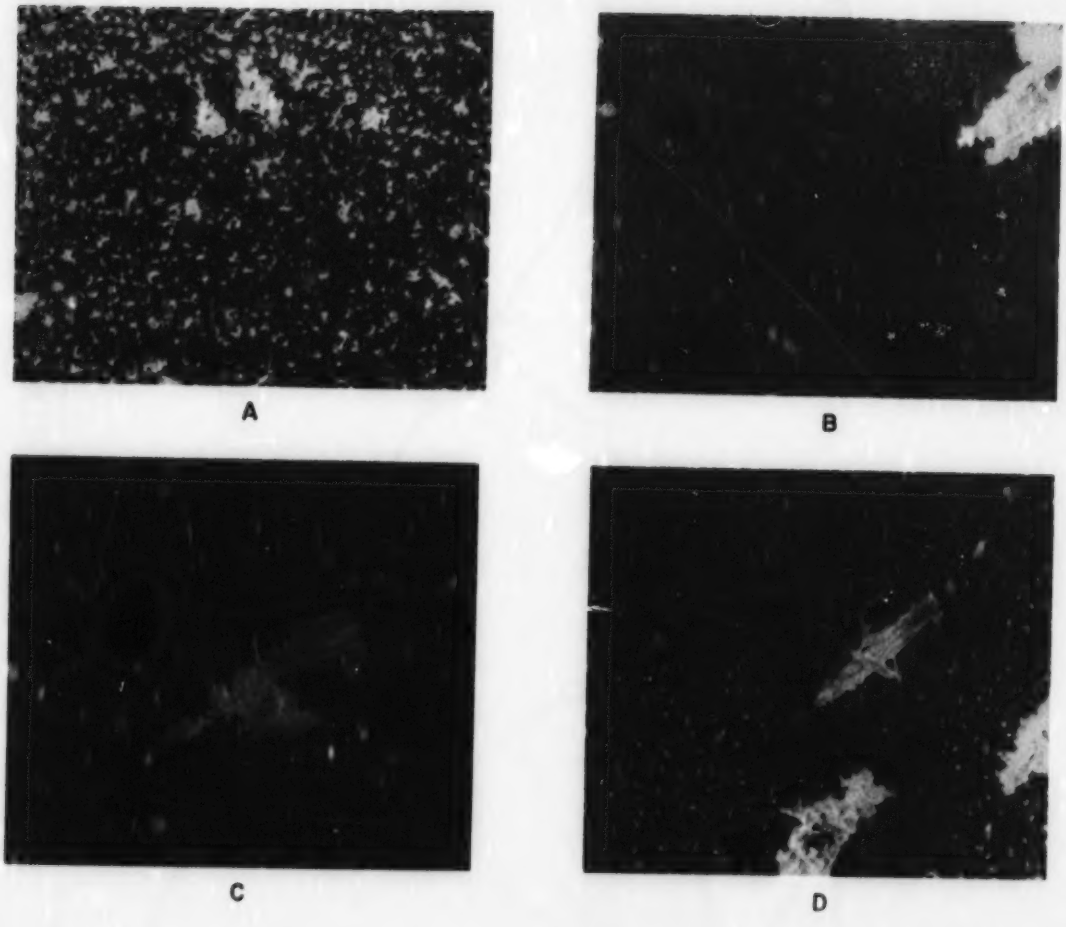


Figure 11: Scanning Electron Microscope Pictures of the Deposition on the Inside Wall of the Exhaust System. Legend: A-Leaded Fuel, 75 inches from exhaust manifold; B-Leaded Fuel, 220 inches from exhaust manifold; C-Unleaded Fuel, 75 inches from exhaust manifold; D-Unleaded Fuel, 220 inches from exhaust manifold. Scale: ⊢ 1 micron.

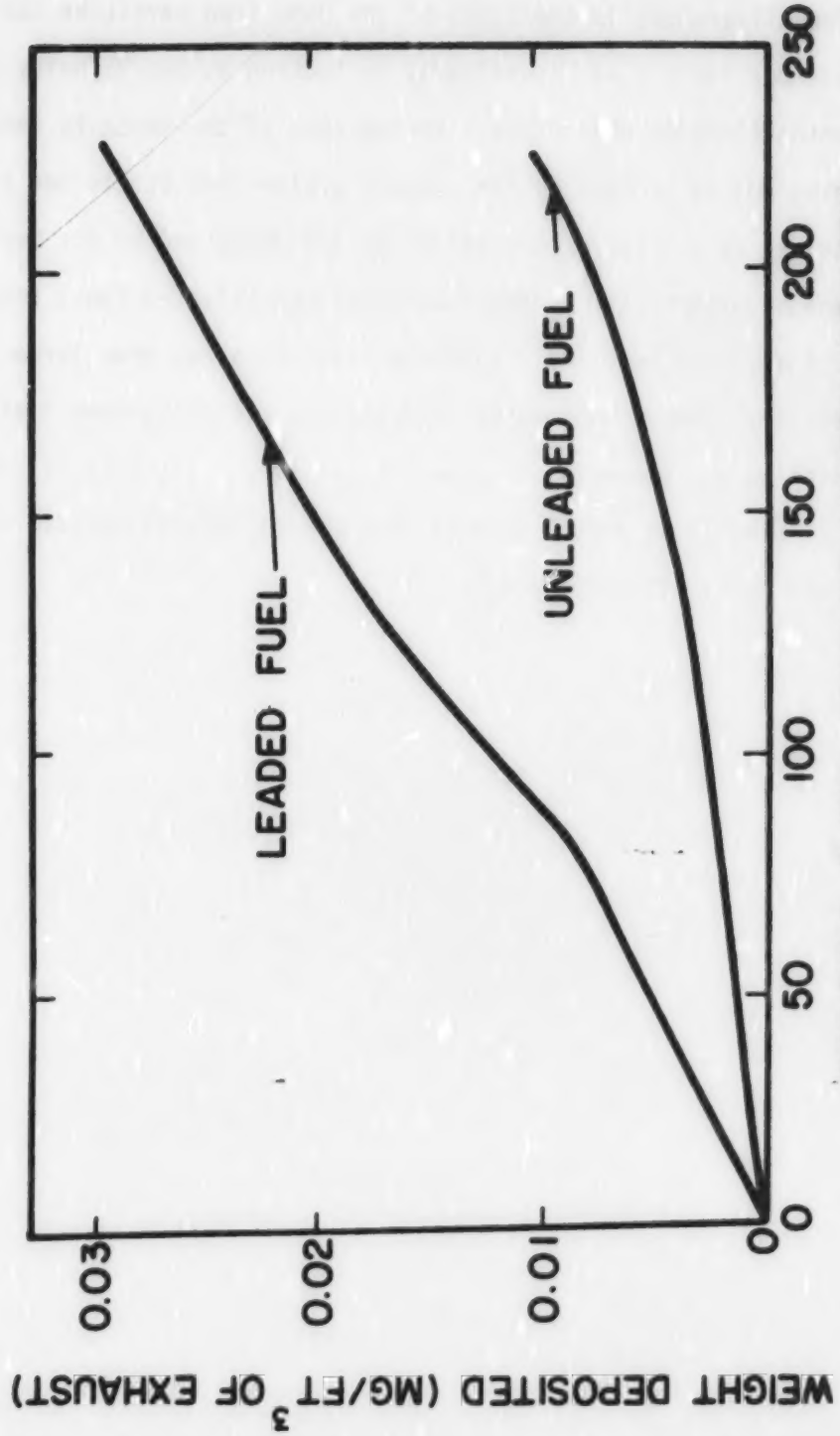


Figure 12: Total Particle Deposition on the Inside Wall of the Exhaust System

The differences in the sizes of the deposited particles using leaded and unleaded fuels were investigated by looking at the deposits utilizing a scanning electron microscope. Photographs of the deposits taken at the beginning and at the end of the exhaust system demonstrate two significant effects: 1) considerably more particles are deposited at the beginning of the exhaust system with leaded fuel than with unleaded fuel, and 2) with leaded fuel, many more small particles are deposited than large ones (Figure 11). These qualitative observations are in agreement with the quantitative measurements presented in Figure 10. It must be recognized, however, that in an actual exhaust system particles accumulate on the walls and flake off periodically.

CHAPTER V

CONCLUDING REMARKS

The experimental results obtained show that both the temperature and lead content of the fuel affect the particle concentration in the exhaust of spark ignition engines. For leaded fuel the particulate concentration decreases from 85 to 450°F, remains constant up to about 700°F, and then decreases sharply. With unleaded fuel, the decrease above 700°F was not observed. The particle concentration with leaded fuel was approximately six times higher than with unleaded fuel.

The size distribution of particles appeared to be insensitive to temperature up to approximately 700°F, but was dependent upon fuel composition. For leaded fuel, the exhaust contained about eight times more small ($<0.35\mu$) particles than for unleaded fuel, but both fuels contained approximately the same number of large ($>0.35\mu$) particles.

Deposition of particles along the exhaust system varied with both the fuel used and with the distance along the exhaust stream. However, during a given period of time the weight of the deposited particles was found to be less than 10% of the weight of the particle concentration in the exhaust stream.

APPENDIX A

ENGINE SPECIFICATIONS

Displacement	350 Cubic inches
Horse Power	255 at 4800 rpm
Carburetor	2 barrel Rochester
Compression Ratio	9.0:1
Bore	4 inches
Stroke	3.48 inches
Spark Plugs	AC R455
Plug Gap	0.035 inches
Point Dwell	30°
Timing	4° B.T.C.

The tests were conducted under the following conditions:

Speed	1800 RPM
Load	24.5 BHP
Air-Fuel Ratio	14.6

Particulate concentrations were measured using Sampling System II at 30, 35, 40, 45, 60, 90, and 120 minutes after starting the engine. No change was observed in these measurements, suggesting a 30 minute warmup period was adequate.

When switching fuels, particle concentrations were measured after operating the engine for 24, 32, 34, 36, and 40 hours. No appreciable change was noted in the concentrations measured at these times. All the data reported was taken after the 32 hour period.

APPENDIX BI

SPECIFICATIONS OF THE MOTOR OIL USED (Ref. 25)

SAE 10W-30

Gravity, °API	29.2
Flash, °F	415
Pour, °F	-30
Cycle C Stable Pour, °F	-30 SP
Viscosity, SUS	
-20°F, CCS	57,000
0°F, CCS	10,200
100°F	310
210°F	64.3
Viscosity Index	177
Color, ASTM	3-3.5
Carbon Residue, %	1.15
Sulfated Ash, %	1.00
Copper Corrosion, ASTM	1b
Phosphorus, % wt.	0.17
Sulfur, % wt.	0.55
zinc, % wt.	0.19
Boron, % wt.	0.02
Magnesium, % wt.	0.12
Nitrogen, % wt.	0.07
TAN, D664	3.5
TBN, D664	6.0
TBN, D2896	7.5
Foam, ml	
70°F, Tend. Stab.	0-0
210°F, Tend. Stab.	10-0
70°F, Tend. Stab.	0-0

APPENDIX BII

PHYSICAL PROPERTIES OF THE LEADED FUEL USED (Ref. 25)

AMERICAN Regular Gasoline

Distillation:	
Initial, °F	85
10%, °F	108
50%, °F	197
90%, °F	324
End Point, °F	363
Loss, %	2.0
Recovery, %	97.0
Residue, %	1.0
% Off @158 °F	33.4
Gravity, °API	62.3
Reid Vapor Pressure	10.9
Color	Bronze
Doctor Test	Sweet
Sulfur, %	0.11
Gum, ASTM D-381	2.2
Copper Strip, 3 hours @ 122°F	1 a
Octane, Research	95.7
Tetraethyl Lead, ml/gallon	2.4

APPENDIX BIII

PHYSICAL PROPERTIES OF THE UNLEADED FUEL USED (Ref. 25)

INDOLENE Motor Fuel HO III

API Gravity	59.1
Distillation, °F:	
Initial Boiling Point	89
10% Evaporated	131
50% Evaporated	230
90% Evaporated	330
Maximum	390
10% Slope	3.0
Reid Vapor Pressure	9.0
Oxidation Stability, Minutes	600+
Gum, mg/100 ml	1.4
TMEL, gms. Lead/Gallon	0.02
Sulfur, Weight, %	0.05
Olefin, %	3.7
Aromatic, %	30.0
Saturates, %	66.3
Octane, Research (Clear)	98.0
Octane, Research (3 cc TEL/gal.)	105.0
Sensitivity (Clear)	9.7
Sensitivity (3 cc TEL/gal.)	8.4
Phosphorus, Grams/Gallon	0.01

APPENDIX C

Special filter holders were designed and constructed to withstand the temperatures encountered in the experiments. The exhaust system filter (F_1) is shown in Figure C-1, and the design of the sampling system filters (F_2-F_5) is presented in Figure C-2.

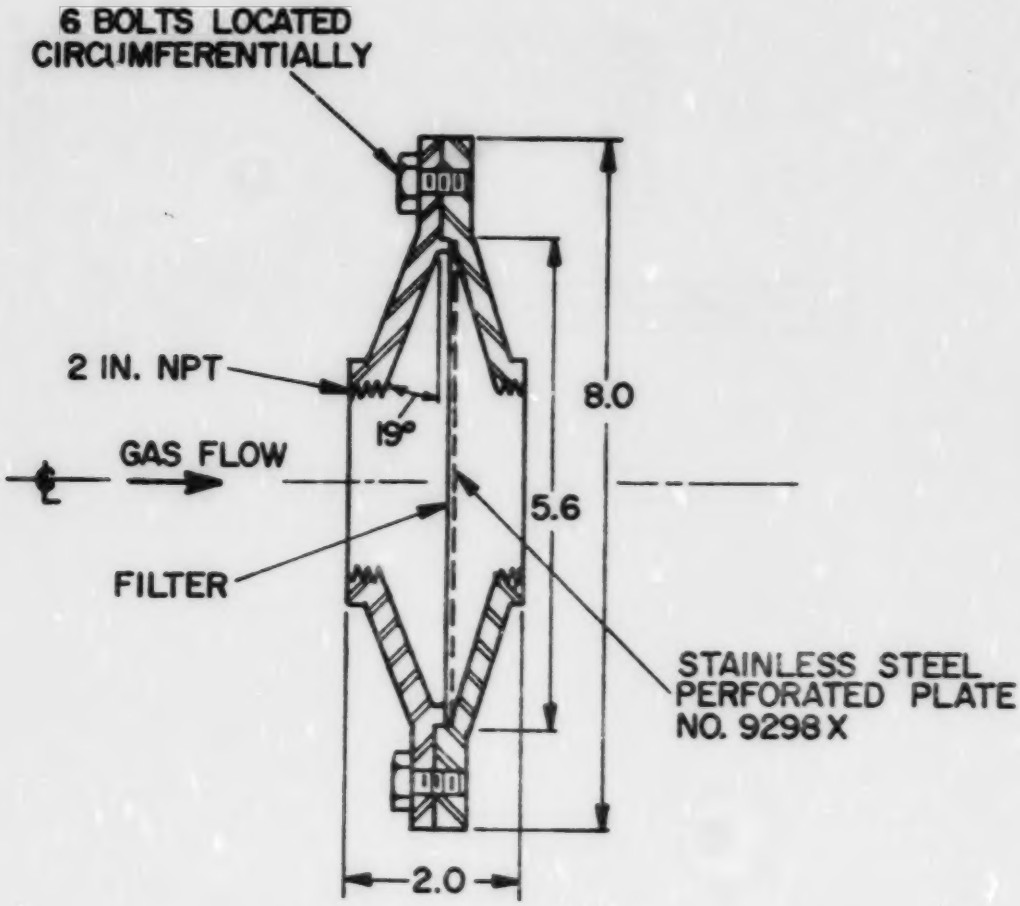


Figure C-1: Exhaust System Filter Holder
Material-Stainless Steel

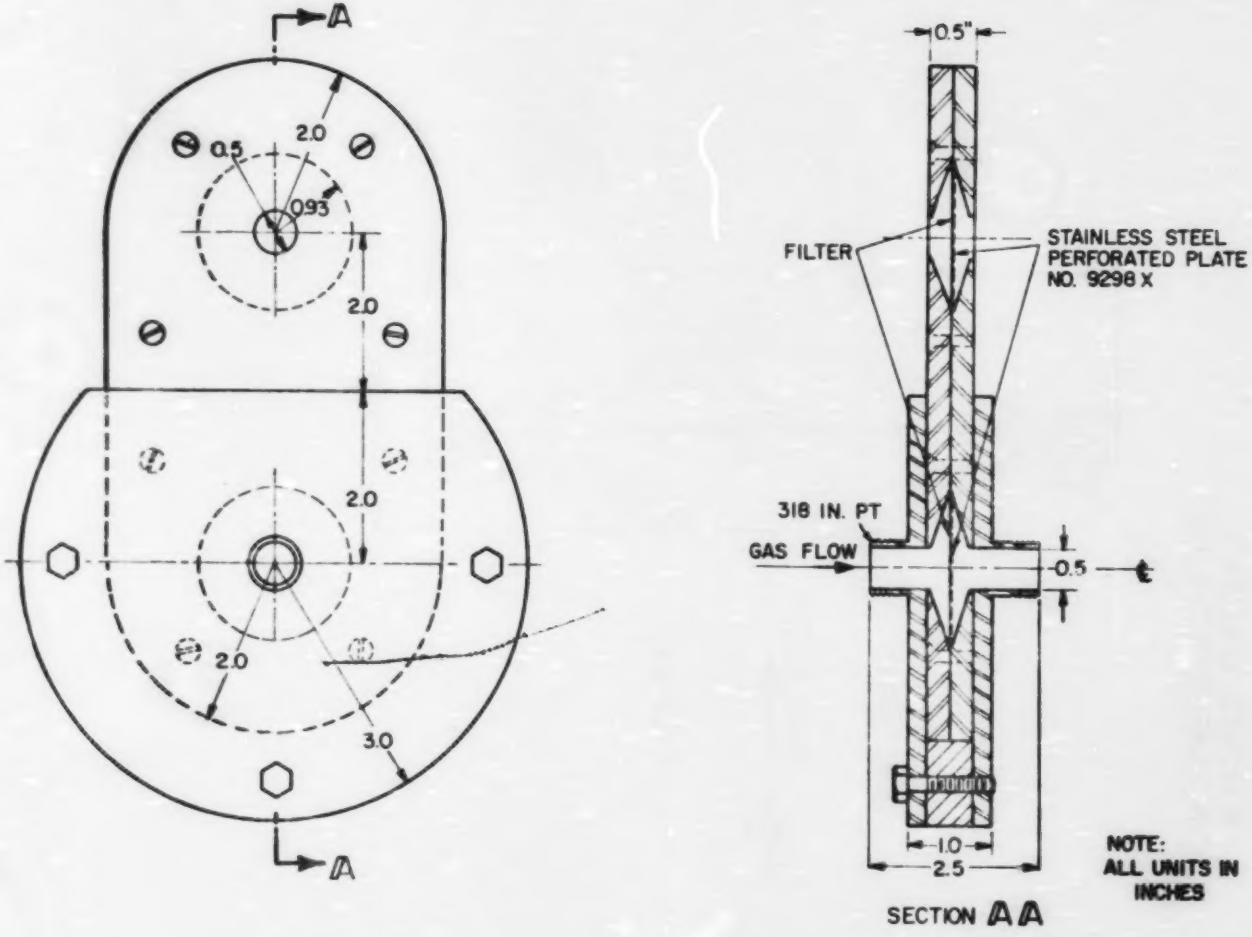


Figure C-2: Sampling System Filter Holder. Material - **Stainless Steel**

APPENDIX D

The Andersen Sampler collects and sizes particles by inertial means. The sampler consists of eight plates with varying size holes which collect particles of the sizes shown in Figure D-1. The solid line in Figure D-1 represents the manufacturers specifications, and the dashed line an extension to higher flow rates by Hu(ref. 26).

Since collection is due to the inertia of the particles, both particle density and gas temperature have an effect on the size collected by the sampler. The effect is accounted for by multiplying the size collected as given in Figure D-1 by a correction factor for density and temperature as given in Figures D-2 and D-3.

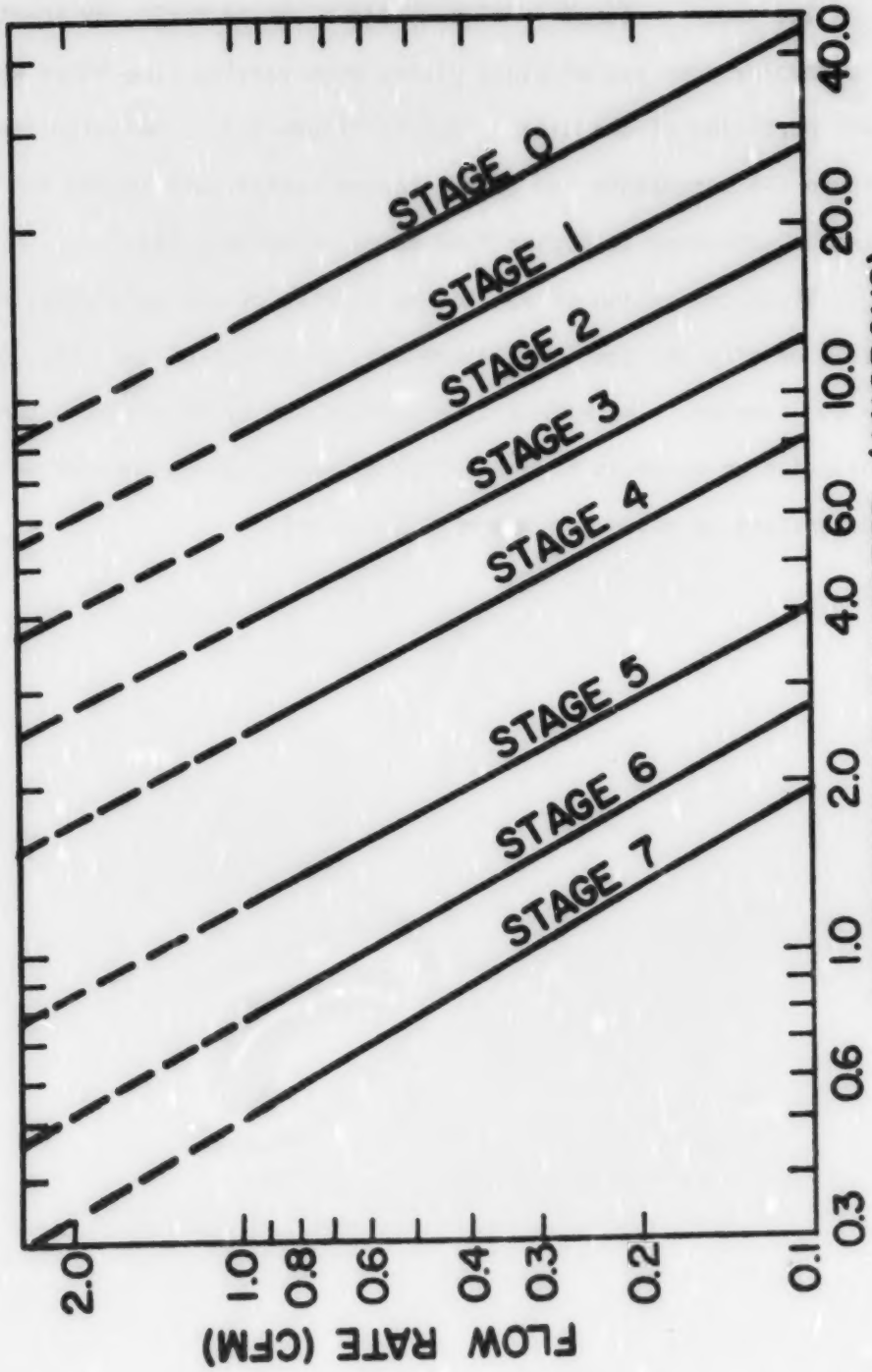


Figure D-1: Aerodynamic Diameter of Particles Collected Versus Flow Rate Through Andersen Sampler.
⊢ Manufacturers specifications (ref. 27), ⊢ - - ⊣ Hu (ref. 26)

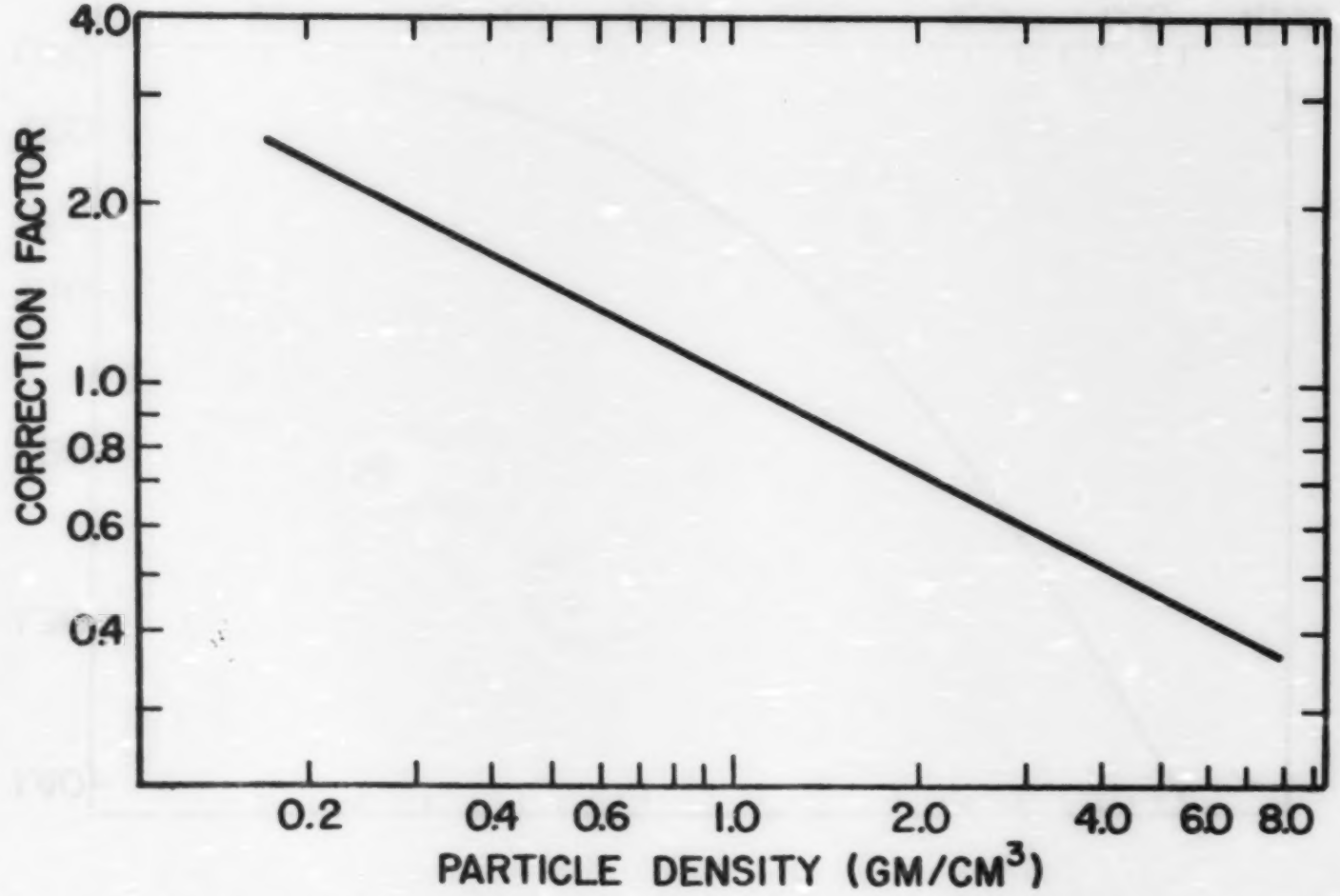


Figure D-2: Particle Density Correction Factor for Aerodynamic Size of Particles Captured by Andersen Sampler (ref. 27)

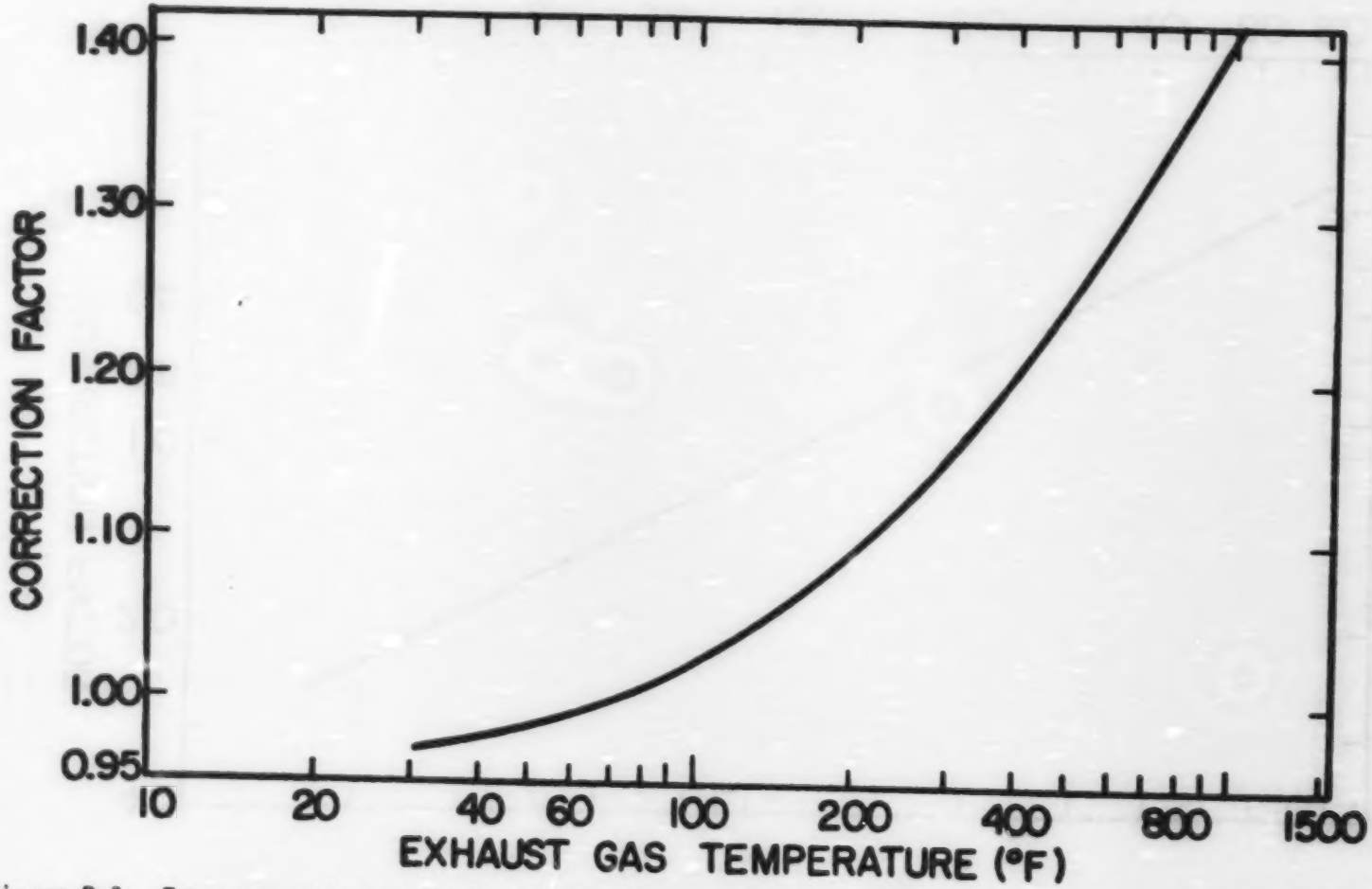


Figure D-3: Temperature Correction Factor for Aerodynamic Size of Particles Captured by Andersen Sampler (ref. 27)

APPENDIX E

Previous investigators have indicated that most of the lead emitted by spark ignition engines is in the form of PbCLBr. The vapor pressure of this compound is unknown but is similar to the vapor pressures of $PbCL_2$ and $PbBr_2$. The vapor pressures of these compounds are presented in Figure E-1.

PbCLBr will condense when the vapor pressure is less than the partial pressure. The partial pressure of PbCLBr in the exhaust is 3.5×10^{-4}mm of Hg, assuming all the lead available is converted to this compound. According to Figure E-1, condensation of this compound should occur at temperatures of 630-690°F.

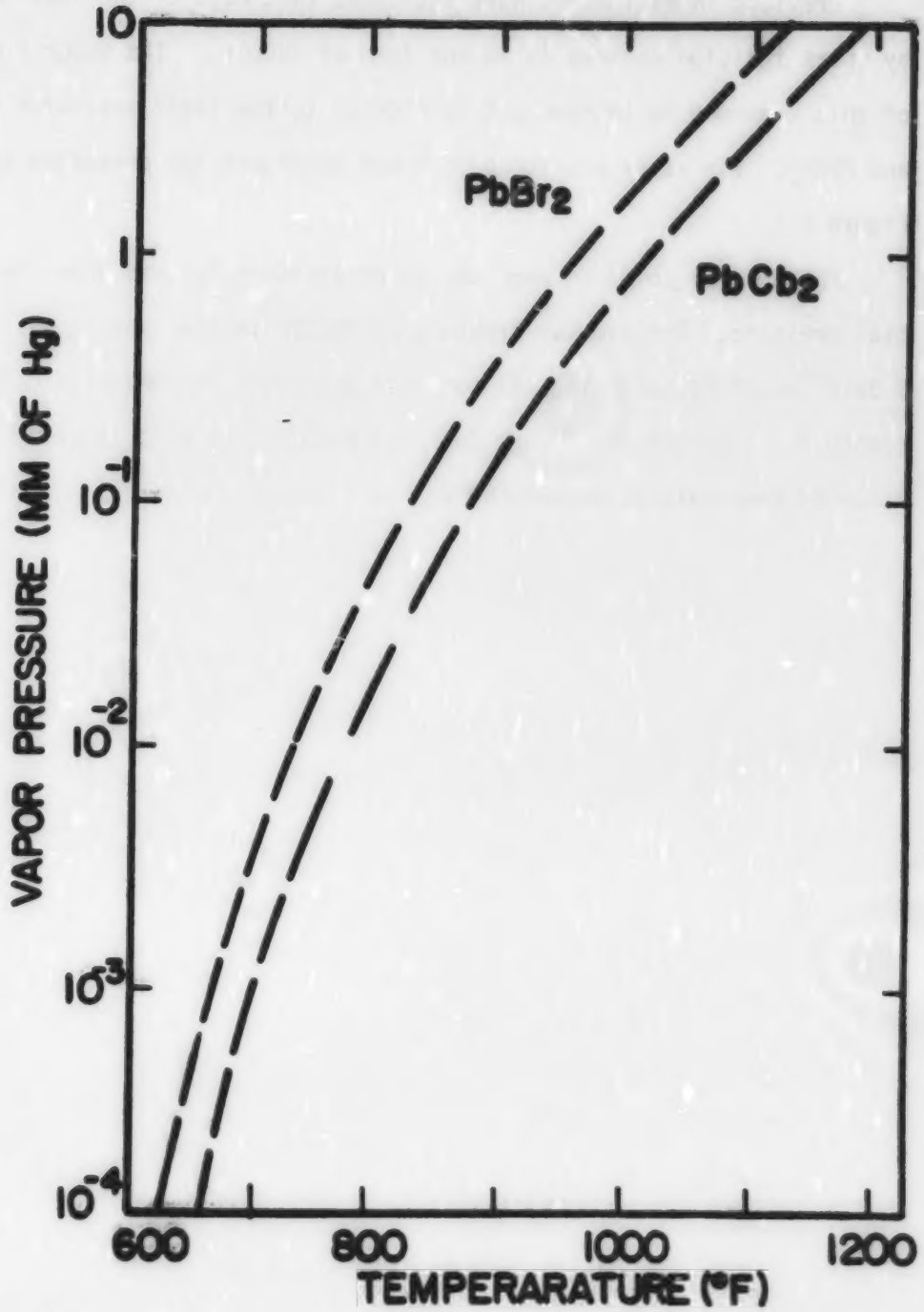


Figure E-1: Vapor Pressure of Lead Chloride and Lead Bromide (ref. 28)

APPENDIX F

The data forming the basis of Figures 8 and 9 and Table IX are presented in tabular form in this appendix. The notation used in this appendix is as follows:

X - sampling location, distance from exhaust manifold (in.)

T - temperature at sampling location (°F)

W_i - weight of particles collected on different stages of the Andersen sampler ($i = 0, 1, 2...$) (mg)

W_3 - weight of particles collected on filter F_3(mg)

Q_3 - flow through the Andersen Sampler in one hour for leaded fuel and two hours for unleaded fuel (ft^3)

W_2 - weight of particles collected on filter F_2(mg)

Q_2 - flow through filter F_2 in ten minutes (ft^3)

NC - natural convection

FC - forced convection

T_4 - temperature of filter F_4 (°F)

W_4 - weight of particles collected on filter F_4(mg)

T_5 - temperature of filter F_5(°F)

W_5 - weight of particles collected on filter F_5(mg)

Q_{II} - flow through System II (ft^3)

t_{II} - test duration for System II (min)

Q_a - air flow through System III (ft^3)

Q_g - exhaust gas flow through System III (ft^3)

t_{III} - test duration for System III (min)

W_6 - weight of particles collected on filter F_6(mg)

T_6 - temperature of filter F_6 (°F)

TABLE FI

Sampling System I

Leaded Fuel

X	T	W_o	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_3	Q_3	W_2	Q_2	Remarks
67	820	0.46	0.49	0.30	0.29	0.35	0.23	0.45	1.05	17.5	50.9	4.16	8.2	NC
105	690	0.83	1.74	0.53	0.39	0.35	0.23	0.30	0.45	24.4	53.5	3.7	5.7	NC
150	570	0.25	0.38	0.35	0.21	0.14	0.19	0.26	0.44	28.6	56.1	4.6	8.9	NC
177	535	0.43	0.31	0.23	0.26	0.30	0.14	0.18	0.66	20.9	52.6	4.41	8.6	NC
202	510	0.52	0.23	0.41	0.32	0.18	0.09	0.31	0.37	31.6	55.8	3.93	7.9	NC
227	490	0.48	0.48	0.33	0.28	0.24	0.12	0.25	0.57	39.7	76.1	6.8	9.8	NC
67	750	0.63	0.39	0.18	0.16	0-05	0.04	0.05	0.01	10.31	81.4	2.1	9.1	FC
105	620	0.63	0.46	0.33	0.36	0.18	0.15	0.30	0.52	20.8	53.7	5.63	7.9	FC
150	520	0.48	0.34	0.19	0.14	0.22	0.16	0.24	0.38	33.4	71.2	7.35	11.6	FC
177	490	0.33	0.37	0.29	0.23	0.14	0.14	0.29	0.49	31.6	69.4	6.43	9.9	FC
202	470	0.54	0.41	0.16	0.19	0.21	0.20	0.23	0.41	29.8	74.6	5.98	8.7	FC
227	450	0.48	0.36	0.33	0.34	0.27	0.15	0.22	0.35	30.2	81.1	6.35	8.7	FC

TABLE FII

Sampling System I

Unleaded Fuel

X	T	W_o	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_3	Q_3	W_2	Q_2	Remarks
67	820	0.65	0.53	0.53	0.54	0.60	0.37	0.34	0.36	1.40	59.3	0.50	9.7	NC
105	690	0.93	0.73	0.80	1.18	0.99	1.30	2.09	2.59	1.57	94.5	0.74	10.3	NC
150	570	0.46	0.63	0.51	0.39	0.65	0.42	0.24	0.61	2.55	121.0	0.30	5.2	NC
177	535	0.54	0.63	0.58	0.74	0.48	0.51	0.54	0.45	2.16	120.4	0.83	9.5	NC
202	510	0.48	0.49	0.38	0.44	0.28	0.13	0.25	0.40	2.20	55.9	0.68	9.5	NC
227	490	0.68	0.54	0.68	0.84	0.75	0.53	0.45	0.50	1.88	128.9	0.70	9.4	NC
67	750	0.41	0.32	0.56	0.42	0.63	0.64	0.39	0.55	2.36	121.4	0.69	9.1	FC
105	620	0.53	0.29	0.38	0.49	0.67	0.39	0.25	0.40	5.19	100.2	0.61	9.6	FC
150	520	0.38	0.26	0.13	0.14	0.10	0.03	0.10	0.22	2.54	80.9	0.81	8.8	FC
177	490	0.67	0.49	0.48	0.54	0.65	0.38	0.30	0.35	2.55	119.6	0.90	10.6	FC
202	470	0.51	0.24	0.36	0.24	0.57	0.44	0.46	0.32	2.71	126.6	0.95	11.4	FC
227	450	0.15	0.01	0.02	0.05	0.12	0.05	0.11	0.14	2.39	58.1	0.91	9.4	FC

TABLE FIII

Sampling System II

X - 67 inches

Natural Convection

Leaded Fuel

T_4	W_4	T_5	W_5	Q_{II}	t_{II}
825	14.2	450	18.6	61.4	60
820	14.1	540	30.7	63.7	60
820	13.6	705	7.4	71.3	75
820	1.7	680	0.3	3.6	10
824	9.4	720	4.1	28.4	30
820	12.6	610	24.4	58.6	60

TABLE FIV

Sampling System III

X	T	T_6	Q_a	Q_g	W_6	t_{III}	Fuel	Remarks
67	820	91	49.8	6.73	6.5	60	leaded	NC
227	490	86	53.1	6.4	5.4	60	leaded	NC
67	820	88	53.4	4.5	0.7	60	unleaded	NC
227	490	87	55.2	5.0	0.8	60	unleaded	NC

APPENDIX G

SAMPLING RATE AND PARTICLE EMISSION CALCULATIONS

For isokinetic sampling, the velocity of the exhaust stream (V_e) must be equal to the velocity at the inlet of the probe (V_p),

$$\text{i.e.} \quad V_e = V_p \qquad \text{G-1}$$

Assuming the velocity profile is uniform across the cross section of the exhaust system, the exhaust stream velocity can be expressed as

$$V_e = \frac{m_e}{\rho_e A_e} \qquad \text{G-2}$$

where m_e is the mass flow rate of the exhaust gas, ρ_e is the density of the exhaust gas, and A_e is the cross sectional area of the exhaust system. Similarly, the velocity at the probe can be written as

$$V_p = \frac{m_p}{\rho_p A_p} \qquad \text{G-3}$$

where m_p is the mass flow rate through the sampling proble, ρ_p is the density of the sample at the probe, and A_p is the cross sectional area of the probe.

Combining equations G-1, G-2, and G-3, the mass flow rate through the sampling system needed for isokinetic sampling is

$$m_p = m_e \frac{\rho_p A_p}{\rho_e A_e} \qquad \text{G-4}$$

Since the temperature and pressure (and consequently density) at the inlet to the exhaust probe are the same as in the exhaust stream, equation G-4 reduces to

$$m_p = m_e \frac{A_p}{A_e} \qquad \text{G-5}$$

The mass flow rate in the exhaust is equal to the sum of the mass flow rates of the air (m_a) and fuel (m_f) entering the engine:

$$m_e = m_a + m_f \qquad \text{G-6}$$

In this experiment, the engine operating conditions were held constant at a speed of 1800 rpm and a load of 24.5 brake horsepower. At these conditions, m_a and m_f were measured to be 4.03 lbm/min. and 0.276 lbm/min., respectively.

The cross sectional area of the exhaust was 3.14 in.^{2} The cross sectional area of the probe used in these experiments varied as indicated in Table II.

Inserting these numbers in equations G-5 and G-6, the mass flow rate in the probe necessary for isokinetic sampling is

$$m_p = 1.37\ A_p \quad (\text{lbm/min}) \qquad \text{G-7}$$

where A_p is expressed in square inches.

The volume flow rate (Q_p) necessary for isokinetic sampling is

$$Q_p = m_p / \rho \qquad \text{G-8}$$

ρ can be approximated by the density of an ideal gas at standard temperature (t=77°F) and standard pressure (P=14.7 psia)

$$\text{i.e.} \quad \rho = \frac{P}{RT} = \frac{14.7 \times 144}{53.3 \times 537} = .074\ \frac{\text{lbm}}{\text{ft}^2} \qquad \text{G-9}$$

Equations G-7, G-8, and G-9 yield

$$Q_p = 18.6\ A_p \quad (\text{ft}^3/\text{min}) \qquad \text{G-10}$$

The probe used in the majority of these experiments had a cross sectional area of 0.0346 in^2. The corresponding flow rate is $Q_p = 0.645\ ft^3/min$.

The amount of particulates emitted in grams/mile (G) was calculated using the expression

$$G = \frac{C_e Q_e}{S_c} \qquad G\text{-}11$$

where C_e is measured particle emission in grams per cubin foot of exhaust flow, Q_e is exhaust flow rate at standard temperature and pressure in ft^3/hr, and S_c is the automobile speed (miles/hr).

The volume flow rate of the exhaust gas was obtained from the mass flow rate of the exhaust using the expression

$$Q_e = \frac{m_e}{\rho_e} \qquad G\text{-}12$$

where m_e is the mass flow rate of the exhaust gas and ρ_e is the density of the gas. At standard conditions, $\rho_e = \rho$, and Q_e is 58.5 ft^3/min.

S_c is the speed at which a 1970 Chevrolet automobile would travel at an engine speed of 1800 rpm. S_c is obtained from the relationship:

$$S_c = 1800 * R * (2\pi r)$$

where R is the ratio of wheel revolutions to engine revolutions, and r is the radius of the rear tires. For a standard size Chevrolet, R is 3.1 and r is 15 inches (22), giving

S_c = [illegible] miles/hr.

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